

**HYBRID BATTERY-SUPERCAPACITOR
STORAGE SYSTEM FOR POWER QUALITY
ENHANCEMENT IN MICROGRIDS**

BY

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In

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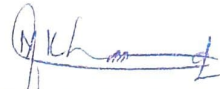
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Dedicated to
My Beloved Parents and Family.

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LIST OF ABBREVIATIONS

BESS	:	Battery energy storage system
DG	:	Distributed generation
DoD	:	Depth of discharge
EMS	:	Energy management system
ESS	:	Energy storage system
EV	:	Electric vehicle
HESS	:	Hybrid energy storage system
ICP	:	Intercranial pressure
Li-ion	:	Lithium-ion battery
L	:	House load requirement
LCO	:	Lithium cobalt oxide
LFP	:	Lithium iron phosphate
LL	:	Local line of the radial distribution network
LMO	:	Lithium manganese oxide
LPF	:	Low pass filter
LTO	:	Lithium titanate

LUT	:	Look-up table
LV	:	Low voltage
LVRT	:	Low voltage ride through
MG	:	Microgrid
ML	:	Main line of the radial distribution network
MPPT	:	Maximum power point tracking
NaS	:	Sodium sulfur battery
NCA	:	Lithium nickel cobalt aluminum oxide
NiCd	:	Nickel cadmium
NiMH	:	Nickel metal hydride
NMC	:	Lithium nickel manganese cobalt oxide
NPIC	:	Nonlinear PI controller
OLTC	:	On-load tap changer
PbA	:	Lead-acid battery
PCC	:	Point of common coupling
PCS	:	Power conversion system

PFC	:	Power frequency control
PSB	:	Polysulfide bromide
PV	:	Photovoltaic system
RDN	:	Radial distribution network
RES	:	Renewable energy source
RoCoF	:	Rate of change of frequency
SCSS	:	Supercapacitor storage system
T	:	Diode temperature
UPS	:	Uninterruptible power supply
VRBF	:	Vanadium redox battery
VRLA	:	Valve regulated lead acid
VSC	:	Voltage source converter
WPT	:	Wireless power transfer
ZEBRA	:	Sodium nickel chloride
ZnBr	:	Zinc bromide

NOMENCLATURE

A	:	Inter-facial area between electrode-electrolyte
α	:	Exponential zone voltage of battery
α_L	:	Active loading constant
B_M	:	Charge/discharge mode of battery
β	:	Exponential capacity of battery
C	:	Output capacitance of converter
C_M	:	Model capacitance of supercapacitor
C_G	:	Thermal motion capacitance of supercapacitor
D	:	Duty ratio of the converter
ΔT	:	Difference between PV's actual and normal temperature
ΔV_s	:	Voltage over-potential
ΔV_{ij}	:	Voltage drop between i^{th} bus and j^{th} bus
ϵ_p	:	Material permittivity
F	:	Faraday constant
f_{lpf}	:	Cut-off frequency of the filter
f_s	:	Sampling frequency

$\mathbf{f_c}$	:	Cross-over frequency
$\mathbf{f_{sw}}$	:	Switching frequency of converter
$\mathbf{G}$	:	Ideal gas constant
$\mathbf{G_{id}}$	:	Inductor current to duty ratio transfer function of converter
$\mathbf{G_{vd}}$	:	Output voltage to duty ratio transfer function of converter
$\mathbf{\Gamma_b}$	:	Maximum capacity of battery
$\mathbf{\Gamma_{sc}}$	:	Electric charge of supercapacitor
$\mathbf{\Gamma_{si}}$	:	Initial amount of charge of supercapacitor
$\mathbf{I_{batt}}$	:	Battery current
$\mathbf{I_{b-ref}}$	:	Reference current of battery
$\mathbf{I_{b-u}}$	:	Uncompensated current from battery
$\mathbf{i_f}$	:	Filtered current of battery
$\mathbf{i_{sc}}$	:	Series current in supercapacitor cell module
$\mathbf{i_{sd}}$	:	Self-discharge of supercapacitor
$\mathbf{I_{sd}}$	:	Leakage current of supercapacitor
$\mathbf{I_{HFC}}$	:	High frequency current component
$\mathbf{I_{LFC}}$	:	Low frequency current component

I_{ph}	:	Photocurrent
$I_{ph,n}$	:	Photocurrent under standard test condition
I_{pv}	:	Output current of photovoltaic system
I_{sat}	:	Saturation current
I_{SC}	:	Supercapacitor current
I_{SC-ref}	:	Reference current of supercapacitor
it	:	Actual charge extracted from battery
I_{t-ref}	:	Total error signal
I_{tsh}	:	Current/temperature coefficient
k	:	Phase margin of k-type compensator
k_B	:	Boltzmann constant
k_p, k_i	:	Proportional gain constant of PI controller
L	:	Converter inductance
N_L	:	Number of electrolyte layers in supercapacitor
N_s, N_p	:	Number of series and parallel supercapacitor cells
n_s	:	Number of series connected photovoltaic cells

$\mathbf{P}_{spv}$	:	Generated output power of photovoltaic system
Ψ	:	Actual irradiance
Ψ_{sh}	:	Nominal irradiance
$\mathbf{P}_G, \mathbf{P}_{Gj}$	:	Generated active power at j^{th} bus
$\mathbf{P}_{ij}$	:	Active power flow from i^{th} bus to j^{th} bus
$\mathbf{P}_L, \mathbf{P}_{Lj}$	:	Active power of the load of j^{th} bus
ρ_b	:	Polarization constant of battery
$\mathbf{Q}_G, \mathbf{Q}_{Gj}$	:	Shunt compensators of generator at j^{th} bus
$\mathbf{Q}_G, \mathbf{Q}_{Gj}$	:	Generated reactive power at j^{th} bus
$\mathbf{Q}_{ij}$	:	Reactive power flow from i^{th} bus to j^{th} bus
$\mathbf{Q}_L, \mathbf{Q}_{Lj}$	:	Reactive power of the load at j^{th} bus
$\mathbf{Q}_{in}$	:	Reactive power injection/absorption by inverter
q	:	Electron charge
$\mathbf{R}_b$	:	Internal resistance of battery
$\mathbf{R}_L$	:	Load resistance
$\mathbf{r}_c$	:	Molar concentration

$\mathbf{r}_m$	:	Molecular radius
$\mathbf{R}_s$	:	Series resistance
$\mathbf{R}_{sh}$	:	Shunt resistance
$\mathbf{S}, \mathbf{S}_{Gj}$	:	Generated apparent power at j^{th} bus
$\mathbf{T}_i$	:	Transfer function of k-type current controller
$\mathbf{T}_{PI}$	:	Transfer function of PI controller
$\mathbf{T}_s$	:	Operating temperature of supercapacitor
$\mathbf{T}_v$	:	Transfer function of k-type voltage controller
$\mathbf{V}_{batt}$	:	Battery voltage
$\mathbf{V}_{ch}$	:	Charge characteristics of battery
$\mathbf{V}_{cvs}$	:	Controlled voltage source
$\mathbf{V}_D$	:	Dynamic voltage zone of battery
$\mathbf{V}_{dc}$	:	DC bus voltage
$\mathbf{V}_{dch}$	:	Discharge characteristics of battery
$\mathbf{V}_{DG}$	:	Terminal voltage of distributed generator
$\mathbf{V}_j$	:	Local terminal voltage at the j^{th} bus

V_{in}	:	Converter input voltage
V_R	:	Node voltage in a radial distribution network
$\hat{V}_S$	:	Sending-end voltage
V_{th}	:	Thermal voltage of photovoltaic system
V_{pv}	:	Output voltage of photovoltaic system
$\hat{V}_R$	:	Receiving-end voltage
V_{ref}	:	Desired reference voltage
V_{SC}	:	Supercapacitor voltage
μ	:	Ideality factor of diode
v	:	Required gain value for k – type compensator
ω_p	:	poles of k- type compensator
ω_z	:	Zeroes of k- type compensator
X_{ij}	:	Reactance between i^{th} bus and j^{th} bus

THESIS ABSTRACT

NAME: Khalid Abdullah Khan

TITLE OF STUDY: HYBRID BATTERY-SUPERCAPACITOR STORAGE
SYSTEM FOR POWER QUALITY ENHANCEMENT
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The intermittency of most renewable (RES) technologies excessively impedes their economical significance as well as critically deteriorates the quality of power supplied to the load. Technological innovations are needed, particularly towards voltage regulation, as it inherently effects the flexibility of RES integration. The emerging concept to utilize the Volt-VAr capability of PV inverter's is suitably applicable for high RES penetration to circumvent a reverse flow of current, system losses and voltage regulation. Especially, in a radial distribution network (RDN) with high R/X ratios of the transmission line and the voltage violation level is significant. Therefore, Volt-VAr control through PV inverter facilitates flexibility of site selection with effective voltage regulation. A local Volt-Var scheme is proposed for active-reactive power

management of PVs. The controller is based on local voltage regulation respective to each PV installation to achieve overall system voltage regulation with minimal active power curtailment. This is tested on a RDN with high PV penetration considering various values for the R/X ratios. The proposed scheme ensures voltage stability of the network and also increases the network hosting capacity towards PV integration.

Further, the prerogative advantage of energy buffering achieved through energy storage system (ESS) significantly mitigates the effects of RES transience and hence effectively increases the proportion of RES integration. However, a range of systematic, technical and economic barriers has stymied higher penetration of ESS. Since a single type of ESS cannot efficiently address voltage regulation combined with other multi-faced challenges associated with RES integration, development of hybrid energy storage system (HESS) and selective utilization of their suitable technical characteristics is more efficient. The applicability of hybrid battery-supercapacitor storage technologies and their mix is targeted to benefit from key features of both technologies towards voltage variation. A novel controller design is developed for HESS based on k - type compensators and a nonlinear PI controller. The formulated controller is tested for voltage regulation in a standalone microgrid and a comparative analysis is presented with a benchmark low-pass-filter controller. The results obtained shows the proposed control technique possess an improved and faster response towards voltage regulation and comparatively has better battery state-of-charge performance.

ملخص الرسالة

الاسم: خالد عبد الله خان

عنوان الدراسة: نظام التخزين الهجين المكون من بطارية و مكثف فائق القدرة لتحسين جودة الطاقة في شبكات الكهرباء الصغيرة.

التخصص: الهندسة الكهربائية

تاريخ الدرجة العلمية: أديأبريل 2020

عند كتابة ملخص ، ضع في اعتبارك مجرد ملخص هو ملخص وصفي قصير لأطروحتك. قد يختلف عدد الكلمات والتغيرات والتقلبات التي تحصل في الطاقة الناتجة عن معظم تقنيات الطاقة المتجددة يؤدي إلى أن تخسر هذه التقنيات قيمتها الاقتصادية، وأيضاً فإنها تؤدي إلى تدهور جودة الطاقة الموصلة إلى الأحمال المرتبطة بشبكة الكهرباء. إذن، هناك حاجة إلى ابتكارات تقنية لحل المشكلة، خاصة باستخدام تقنية تضبط الجهد الكهربائي بين قيمتين معينة وذلك لتحسين مرونة تركيب وتوصيل تقنيات الطاقة المتجددة إلى الشبكة. إن استخدام المفهوم الذي اشتهر مؤخراً باسم فولت-فار، وهو يعتمد على تحويل الطاقة النشطة إلى الطاقة الخيالية باستخدام محولات خلايا الطاقة الشمسية (التي تحول الطاقة الثابتة إلى طاقة مترددة)، لضبط الجهد الكهربائي في مجال معين، استخدام هذا المفهوم في منطقة مليئة أو ستملاً بتقنيات الطاقة المتجددة يساهم في خفض التيار المتجه باتجاه معاكس، وخفض خسائر الطاقة في النظام، وخفض تغيرات وتقلبات الطاقة في النظام، خاصة إذا استخدم هذا المفهوم في شبكات طاقة تعمل باستخدام مولد طاقة واحد وكانت نسبة المقاومة الحقيقية إلى المقاومة الخيالية لخطوط النقل عالية، وكان أيضاً مستوى مخالفة الجهد الكهربائي عالي. لذلك فإن التحكم في قدرة محولات خلايا الطاقة الشمسية لتحويل الطاقة النشطة إلى طاقة خيالية يسهل مرونة اختيار المواقع التي يحصل فيها ضبط للجهد الكهربائي بكفاءة عالية. طريقة الفولت-فار المحلية تستخدم لإدارة نسب الطاقة النشطة والخيالية لخلايا الطاقة الشمسية. جهاز التحكم في هذه الحالة يعتمد على ضبط الجهد الكهربائي بشكل محلي بجانب كل نقطة خلايا شمسية موصلة للشبكة لتحقيق ضبط الجهد الكهربائي الكلي للنظام مع أقل خفض للطاقة النشطة. إن جهاز التحكم هذا تم اختبار أدائه على شبكات كهربائية موصلة بمولد كهربائي واحد وتحتوي على عدد كبير من

نقاط خلايا الطاقة الشمسية، وقد تم اختباره مع قيم مختلفة من نسب المقاومات الحقيقية إلى المقاومات الخيالية. إن هذه الطريقة المقترحة تؤمن الحصول على استقرار للجهد الكهربائي في شبكة الكهرباء وهي أيضا تزيد من قدرة الشبكة على استقبال المزيد والمزيد من خلايا الطاقة الشمسية. إن الفائدة المحصلة من وجود حاجر لتخزين الطاقة في الشبكة وذلك باستخدام نظام تخزين للطاقة هي تخفيف الآثار المترتبة على تقلبات الطاقة بشكل كبير وهي أيضا تزيد القدرة على استقبال المزيد من تقنيات الطاقة المتجددة بكفاءة عالية. ولكن العديد من العوائق التقنية والاقتصادية والممنهجة أدت إلى تقليل القدرة على استقبال الشبكة لعدد أكبر من أنظمة تخزين الطاقة. إن استخدام نوع واحد من أنظمة تخزين الطاقة لا يستطيع أن يضبط الجهد الكهربائي بكفاءة جيدة عندما يكون هناك تحديات أخرى مرتبطة بتوصيل المزيد من تقنيات الطاقة المتجددة، وبالتالي فإن التقدم الحاصل باستخدام نظام تخزين الطاقة الهجين وبالاختيار والوصول إلى خصائصه التقنية المناسبة أدى إلى ضبط الجهد الكهربائي بكفاءة عالية. إن القدرة على تطبيق تقنيات تخزين البطارية-المكثف الفائق الهجينة والخلط بينهما تستخدم للحصول على ضبط للجهد الكهربائي بكفاءة عالية وذلك من خلال استخدام خصائصهم المميزة. ولذلك، فإن تصميم جهاز تحكم جديد تم تطويره في هذه الأطروحة من أجل نظام تخزين الطاقة الهجين بالاعتماد على المعوضات من نوع K وأجهزة التحكم الغير خطية من نوع PI. إن جهاز التحكم المصمم تم اختبار أدائه في ضبط الجهد الكهربائي في شبكات كهربائية صغيرة ومعزولة. إضافة إلى ذلك، فإن دراسة مقارنة تم عرضها في الأطروحة بين أجهزة التحكم المطروحة وأجهزة التحكم الأساسية المعتمدة على مرشحات تمرير منخفضة التردد. إن النتائج التي حصلنا عليها أظهرت أن طريقة التحكم المطروحة قادرة على الوصول إلى استجابة أسرع مع قدرات ضبط متطورة ومتحسنة للجهد الكهربائي، كما أنها أظهرت أيضا أنها قادرة على الحصول على أداء أفضل وعمر أطول للبطارية إذا ما قورنت بنتائج سابقة.

CHAPTER 1

INTRODUCTION

In the subsequent years electric generation, transmission and utilization around the globe will be subjected to preeminent concern due to several reasons, such as, limited fossil fuel resources, incremental electric power consumption, global climatic change, legislation for integrating renewable energy sources (RES), and stochastic properties of RES and their associated problems [1]. The electric power demand is expected to increase by 30% till 2030 in comparison to energy consumption of 2012, mainly due to proliferation of global population [2]. Thus the need for incorporating RES intensified over the past few years leading the researchers and legislates to contribute and innovate in this field, to supply and sustain the increasing electric power needs while preserving global climatic conditions and greener environment for the future generations.

The global electric energy production have, therefore experienced an increased integration of renewable sources, ranging from solar, wind, hydro, tidal, geothermal and biomass with 8.3 % increase in its installed capacity between 2016 and

2017 [3]. In recent decades, photovoltaics (PV) has been prominently used, attributable to its cost reduction, simple installation, modularity, and technological maturity [4]. Subsequently, the applicability of PV has quickly become viable for small scale installations and is considered as the third most implemented renewable sources for power generation, after hydro and wind energy respectively.

Nevertheless, the unpredictable and uncontrollable intermittency of these RES introduces, and or contributes to various power quality degradation in a distribution network. Primarily the challenges associated are demand-generation mismatch, detrimental impact on the voltage and frequency of the power network [5], degrading its reliability [6, 7] and inadvertently limit the feasibility of RES penetration [8]. Voltage regulation, among other technical challenges associated with RES integration, is an important technical aspect that tends to define the allowable limit of RES integration in a power network.

Presently, the concept of microgrid (MG) is extensively adopted for RES integration [9], propagating the flexibility and controllability to establish distributed generation (DG) that is necessary to advocate techno-economic installation of RES. Typically, MG are designed to locally establish exclusive RES control to facilitate a load-following connection between the RES and the grid through energy storage systems, power electronic interfaces and some local loads; and has proved to be highly efficient to economically overcome the transient power generation of RES.

Therefore, the prerogative advantage of energy buffering achieved through en-

Generation Applications	Infrastructure Applications	Cross-cutting Applications
• Bulk Energy Services • Electric Time Shift • Electric Supply Capacity • Renewables Integration • Firming • Curtailment Avoidance • Ancillary Services • Frequency Response & Regulation • Ramping / Load Following • Voltage/VAR Support • Spinning Reserves	• Transmission Services • Network Capacity • Congestion Relief • Reduced loss and maintenance cost • Distribution Services • Network Capacity • Voltage/VAR Support • T&D Upgrade Deferral • Less equipment wear and tear • Increased Hosting Capacity • Area Regulation	• Peak Demand Reduction • Energy Management Services • Time-Varying Rate Management • Demand Charge Management • Reliability Services • Back-up Power • Black Start • System Flexibility • Less start-up and shut-down cost • Reduced GHG emission

Figure 1.1: Application of energy storage systems in various fields of renewable integrated electric network.

energy storage system (ESS) significantly mitigates the effects of RES transience. In addition, ESS is also intensively maintains the power quality of MG, especially in case of standalone and/or islanded conditions. This characteristics facilitates numerous applications of ESS, both at generation and distribution based deployment of RES in a power network as shown in Figure 1.1 and Figure 1.2. However, the scope of a techno-economic installation of ESS, apart from capital cost, operational cost, optimal sizing/siting, reliability and availability, are largely dependent on their respective technical characteristics against a defined challenge associated with RESs integration.

Moreover, a combination of systematic, technical and economic barriers has stymied the significantly higher penetration of ESS over the globe [10]. Despite ongoing developments, there is a lack of cost-effective, mass-produced, and, most

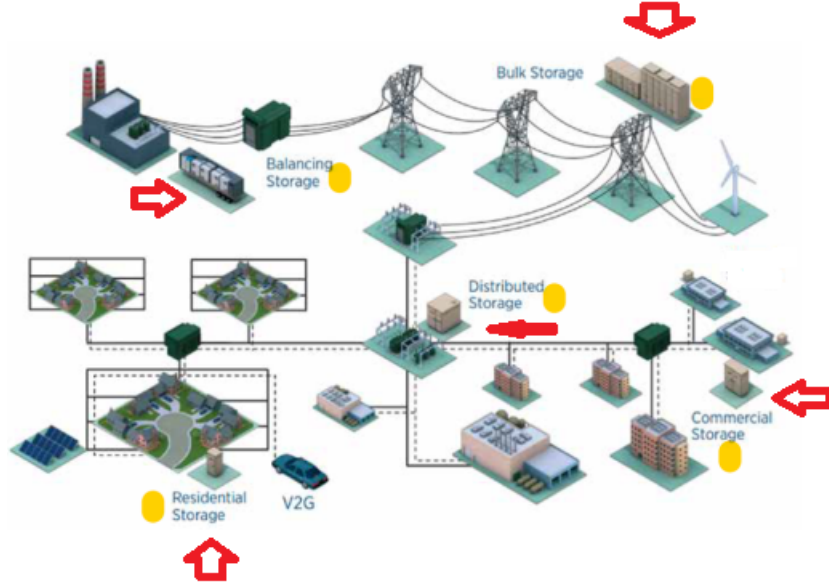


Figure 1.2: Scalability based overview of energy storage systems.

importantly, fully integrated storage solutions. Consequently, this resource and knowledge gap leads to increased energy costs, either seen as initial costs of installation, or as the levelized cost of energy over the estimated lifetime of storage systems.

Pragmatically, choosing the right storage technology for RES integration, its design and optimal-operation is similarly important for the success or failure of any storage project across all steps from its initial design to deployment, operation and end-of-life of a system. Most of the ESS technologies lack the technical properties to solely overcome the vast band of challenges associated to overcome the challenges perceived in MGs, for instance, the commonly used battery energy storage technologies even though, highly feasible for techno-economic deployment of RES, are detrimentally impacted and oversized in case of peak abrupt tran-

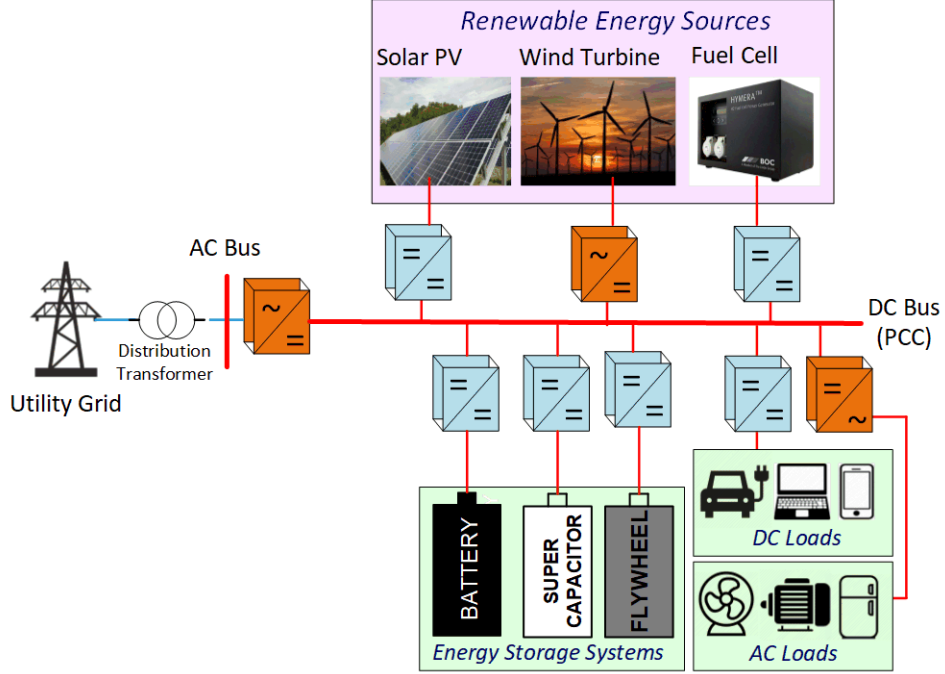


Figure 1.3: Typical DC-microgrid integration to the AC distribution network.

sient load/generation disturbances and variations. Among other solutions, hybridization of storage technologies has been proposed to exploit the dominant characteristics of the energy storage to overcome various issues faced in renewable integration [11–15].

Among various recommendations of ESS hybridization such as lead-acid and lithium battery energy storage systems (BESS), flywheel-BESS BESS-superconducting magnetic energy storage and BESS-supercapacitor energy storage system (SCSS); the high degree of characteristic complementarity between BESS and SCSS facilitates numerous feasible solutions in DC-microgrid based RES integration [16, 17]. In a DC microgrid, the point of common coupling (PCC) uses power electronic devices to facilitate the interfacing of numerous distinctive components such as the numerous RESs, loads and the energy storage devices. In accordance, volt-

age regulation is pertinent for optimized interconnection as well as, to maintain the stability of grid-interconnection through inverters. Therefore, abrupt variations in the DC microgrid pertaining to the load requirement and RES generation will inherently effect the efficacy of the integration [18]. The commonly used DC capacitors at the PCC are unable to maintain the degree of demand-generation based voltage variation [19]. In this case, hybrid BESS-SCSS is considered to be among the best solution [20,21]. The associated concept regarding this HESS in DC voltage regulation lies in the power allocation, that is, compensation of the long-term average power demand by BESS and allocating the short-term abrupt peak power variation to the SCSS. Nevertheless, control strategy implemented for power allocation governs the degree of utilization of this HESS features. Firstly, the control technique should maintain the current level of BESS, so as to increase its operational viability and lifetime by mitigating the BESS current stress. At the same time, the switching of SCSS should correspond to the abrupt load-generation variation for regulate both voltage deviation and magnitude.

On the other hand, high penetration of RES, especially rooftop PVs, on low and medium distribution networks impacts the operation of the grid. Primarily, the passive nature of conventional network that follows a unidirectional power flow becomes a bidirectional active network. In addition, the PV being closely installed to the loads imposes a major operational obstacle due to voltage violation and subsequent reverse power flow [22]. Additionally, the rapid nature intermittency of RES output combined with unpredictable load variation negatively impacts the

traditional on-load tap changer (OLTC) and capacitor banks, during the process of voltage regulation [23]. Furthermore, these type of voltage violation are highly dependent on the placement of the PV as well as the dynamics of the distribution network. The voltage rise occurs exclusively at specific nodes on which the PV is installed.

An analysis of the relations between RESs and the distribution network is pertinent for understanding their respective behaviours for outlining the parameters required to establish a stable and economical operation of renewables in a power network. Generally, power quality enhancements designed for distribution networks are based on the network being passive, that is, power flows from a higher voltage level to low voltage level. A significant network behavioral change occurs with the integration of distributed renewable integration, primarily due to the shift of the distribution network from a passive to active network with a bi-directional power. Though advantageous in some respect, requires novel approach and advanced power management techniques to harness their maximum benefits and support increased penetration.

For an effective voltage regulation, volt-var management strategies through PV inverters have been proposed [24–26] that provide localized nodal voltage regulation. This concept proposes the injection or absorption of reactive power at the inverter terminal. Further, in contrast to utility based reactive power compensation methods (OLTCs, capacitors banks, static Var compensators, etc) that requires complex algorithm and planning for optimal size and placement,

the alternative PV inverters based reactive power compensation provides a more flexible solution especially in case of rapid proliferation of RES in the distribution network. Furthermore, this methodology, with appropriate coordination obviates the need for complex communication or coordination among the inverters [27].

1.1 Motivation

Since energy storage system constitutes an important factor towards these goals, but will requires extensive investment. Subsequently, there is a need for characteristics classification of energy storage technologies, especially for harsh climatic conditions of Saudi Arabia. Since, the Kingdom ambitiously committed to integrate large-scale RES for electric power generation over the next decade. In accordance, considering rapid degradation as well as inferior operational objectivity of various energy storage technologies, identification and recommendation of suitable ESS is pertinent for techno-economic significance. This review aims to serve as a basic foundation for the coming researchers and utility operators for addressing, adopting and establishing a long-term economical RES integration.

Similarly, the complementary characteristics of battery-supercapacitor HESS expedites its application in various challenges and optimization in the filed of electrical and electronics. The intrinsic characteristics achieved with this HESS is highly versatile specifically in the field of electric power generation through transient RES in terms of output power smoothing, fault support, voltage regulation and various other improvement of power quality. Nevertheless, the potential of this HESS is yet to be explored in other field. Therefore, a comprehensive review on the various applications of HESS is needed to identify its current technological advancements that will be instructive for future research development and implementation.

As discussed in previous section, the importance and the need for voltage

regulation in various stage of power system network, towards achieving high penetration of RES. The proposition of battery-supercapacitor HESS, though feasible, is highly dependent on the power allocation strategy. The magnitude and deviation of voltage at the DC bus can be achieved with a decoupled based control strategy, that can exclusively utilizes the dominant characteristics of BESS and SCSS. Based on most the existing control technique proposed, the transient response of SCSS is the key feature that determines the efficacy of the hybridization of these storage technologies. Mostly, the interdependent power allocation technique employed for BESS and SCSS suffers from slow dynamic response of BESS that inherently for current and voltage sensing devices and subsequently the SCSS transient response towards effective mitigation of deviated voltage magnitude and time period. Hence, an instructive design is needed based on circuit knowledge and energy storage characteristics that can be achieved with a decoupled power allocation technique.

Furthermore, considering large scale renewable integration, a meticulous voltage regulation methodology is required for nodal voltage regulation that drastically impacts the voltage profile in low and medium distribution networks with high renewable penetration. The concept of PV inverter volt/var management technique needs extensive research contribution while considering various factors, such as R/X ratios, load variations and dynamics of the distribution network with high level of renewables.

1.2 Thesis Objectives

The objectives of this research is listed below.

1. A comparative evaluation of hybrid energy storage technologies for power quality improvement and their regional classifications for Saudi critical climate conditions
2. A comprehensive literature review on various applications of hybrid battery-supercapacitor energy storage system such as battery-supercapacitor
3. Power quality improvement pertaining to voltage restoration and reduced peak voltage magnitude through battery-supercapacitor hybrid energy storage system in a renewable based DC microgrid.
4. Active-reactive power management in a radial network consisting of high PV penetration through reactive power capability of PV inverters.

1.3 Thesis Organization

The thesis is organized under a total of 5 chapters, their brief illustrative content is as follows:

Chapter 2 gives a detailed background and in depth applications of battery energy storage system to overcome the technical challenges associated with renewable power networks with recommendations considering high ambient temperature of Saudi Arabia. Further, the need of hybridization of energy technologies is also presented with in-depth discussions. In accordance, a comprehensive review is also presented to outline the present advancement achieved by battery-supercapacitor energy storage system, and their applicative scope in the field of solar, wind, electric vehicles and wireless power technology. Thereby, outlining the future scope and needed research gap for future consideration.

Chapter 3 proposes a power allocation strategy between battery and supercapacitor hybrid energy storage system. This chapter includes the modelling, application and comparative analysis of the proposed controller and its design.

Chapter 4 presents a technique for coordinated active-reactive power management through PV inverters. This chapter discusses the need for localized volt/var management and further outlines the design and controller. Furthermore, the development and analysis are presented based on the obtained results.

Chapter 5 Includes the conclusion on the research work done and its future scope.

CHAPTER 2

LITERATURE REVIEW

2.1 Battery energy storage systems

Ideally, power system researchers perceive and innovate on the basis that an ESS possesses high energy density, high power density, optimal response time, efficient reaction time to effectively compensate for disturbances in RES power networks in a plausibly techno-economic way. Many different applications of ESS has been identified to enhance the operation and performance of RESs [28–30]. For instance, it can store the uncontrollable, surplus power produced by RESs and supply at deficient periods of power production, eliminating over-sizing and power curtailment of RESs [31,32]. Further in wind energy system, ESS can be employed for low voltage ride through (LVRT), voltage control support and mitigation of fluctuation power, resulting in smooth power output [33–35]

Despite ongoing developments, there is a lack of cost-effective, mass-produced, and, most importantly, fully integrated storage solutions [36]. In addition, nu-

Table 2.1: Technical characteristics of energy storage systems

	NiCd	Lead-acid	Li-ion	NaS	ZEBRA
Power rating (MW)	0-40 [39]	0 - 20 [40, 41]	0 - 0.01 [40, 41]	0.05 - 8 [40, 41]	0 - 0.3 [40]
Energy density (Wh/L)	60-150 [40]	50 - 100 [42]	200 - 500 [40]	150 - 250	150 - 180 [42]
Power density (W/L)		10 - 400 [40]			220 - 300 [40]
Specific energy (Wh/kg)	35-60 [39]	30 - 50 [40-42]	150 - 350 [40]	150 - 240	100 - 120 [39]
Specific power (W/kg)	140-180 [39]	75 - 300 [40, 41]	500 - 2000 [40]	150 - 240 [39, 41]	150 - 200 [39]
Power capital cost (\$/kW)	500-1500 [30]	300- 600 [30, 39]	1200 - 4000 [30, 39]	1000 - 3000 [30, 39]	150 - 300 [30, 39]
Energy capital cost (\$/kWh)	800-1500 [30]	200 - 400 [30, 39]	600 - 2500 [30, 39]	300 - 500 [30]	100 - 200 [30]
Capital cost (¢/kWh-per-cycle)	20-100 [40]	20 - 100 [30, 39]	15 - 100 [30, 39]	8 - 20 [30, 39]	5 - 10 [30, 39]
Reaction time (ms)	ms [30]	3 - 5 [30]	3 - 5 [30]	3 - 5 [30]	
Self-discharge rate (% per-day)	0.2-0.6 [30]	0.1 - 0.4 [30]	10 [30]	0.1-0.4 [30]	20 [30]
Discharge time	sec-hrs [40]	sec - hr [40]	min - hr [40]	sec - 10 hr [40]	2 - 5 hr [40]
Life cycles	2000-3500 [30]	1000 - 2000 [40, 43]	1000 - 10,000 [40, 43]	2500 - 4500 [40, 43]	2500 - 3000 [40, 43]
Lifetimes (years)	10 - 20 [30]	5 - 15 [39, 41]	5 - 20 [39, 41]	15 - 20 [39, 41]	10 - 14 [39, 41]
Overall Efficiency	0.6 - 0.83 [30]	0.70 - 0.90 [30]	0.85 - 0.95 [30]	0.75 - 90 [30]	0.86 - 0.88 [30]
Temperature operating range (°C)	-5 to 45 [39]	-5 to 40 [41]	-30 to 60 [44, 45]	270 to 350 [41]	-40 to ~ 70 [40]

merous distinct problems associated with RES for instance, poor power quality, meager load following, generation-load mismatch, voltage deviation, frequency instability and, intermittent output power cannot be techno-economically achieved by a sole ESS technology. Consequently, this resource and knowledge gap leads to increased energy costs, either seen as initial costs of installation, or as the leveled cost of energy over the estimated lifetime of storage systems. At the same time, the ongoing, and in some cases rapid, technological developments in the fields of material sciences and chemical engineering means that the future shape of energy storage has yet to be set and is expected to change in the short and long-term [37, 38].

Usually due to high energy density, relative portability and technological maturity battery energy storage systems (BESS) are popularly preferred for RES applications in power systems [46]. Various commercialized battery technologies such as, Lead-acid (PbA), Nickel metal hydride (NiMH), Lithium ion (Li-ion), nickel cadmium (NiCd), sodium sulphur (NaS) and flow batteries are being currently developed and tested for feasibility in the application of RESs; the technical

characteristics are given in Table 2.1.

2.1.1 Lead-Acid Battery

Lead-acid batteries are widely implemented as power engine starters in vehicles. These BESS are produced as a relatively low cost owing to its commercialized mature technology. Additionally, this technology provides is established as efficient, reliable with strong surge capabilities. However, this technology is limited to many energy management services due to its relatively low life cycle to other technologies. Nonetheless, they are applicable to provide spinning reserves and other back-up power supply systems. Among the two typical types, valve regulated lead acid (VRLA) battery is the low-maintenance solution as opposed to flooded PbAs which requires monthly maintenance of distilled water [28]; this imposes a major limitation even though flooded PbAs have good potential in RESs application for temperatures above 30°C [47]. The main favourable characteristics for applications in RESs are high energy efficiency, low investment-maintenance cost and low self-discharge rate that helps towards economic feasibility. Furthermore, the ability of continuous discharge-ability (as high as 80 % for some deep-cycle lead acid batteries), is highly favourable for small scale grid-integrated-commercial RES applications [48].

Nevertheless, characteristics such as low energy density, slow charging rate, low depth of discharge (DoD <20%) low life cycle, environmentally detrimental and poor performance at extreme ambient temperature [49]; thus, even though PbAs

can effectively perform services like frequency support, integration of RESs and other grid-scale applications, other BESS technologies are currently considered for these applications [50].

2.1.2 Nickel-Cadmium Battery

Nickel-cadmium based batteries have been extensively used for stationary as well as portable applications. They provide identical technical characteristics as PbAs but with improved life cycle and specific energy, less maintenance cost and does not require thermal management to maintain its specific operating temperature, but at a higher investment cost [51] and cadmium toxicity causes environmental concerns comparable to PbA batteries.

In addition, the maximum capacity and life cycle being are subjected to “memory effect”; where the battery is required to be fully charged even after a partial discharge, otherwise maximum capacity of the battery incurs rapid decrements [52]. This is a major drawback that significantly makes it unreliable for long term or large-scale application in RESs integration. Although, NiCd batteries are primarily preferred to portable electronics, there are a few grid-scale services applications. They can effectively serves as spinning reserves and support during black-start process.

On the other hand, NiMH batteries is a much more suitable alternative and have much lower memory effect. In addition to low maintenance requirement, this technology comparatively possesses longer life cycle and higher energy density (25

- 30 % greater than NiCd batteries). Therefore in terms of applications to RES, they comparatively provide durability, better reliability, ensures continuous power supply and with low series resistance and are ideal to compensate the pulsed power requirements of the system [53]. However, these batteries are projected to be applicable as ESS in electric vehicles (EV), but in case the case of RES integration characteristics such as severe self-discharge (5 - 20% per day) and memory effect impose a unreliable security threat both technically and economically [44].

2.1.3 Sodium-Sulphur Battery

The operational stage of sodium-sulfur (NaS) battery occurs in molten state. An external heating is required for operational initialization, however, charge and discharge that are operated at temperatures above 300°C can be maintained with internal heating. In comparison to other counter part technologies, NaS battery have relatively high energy density, life cycle, efficiency with deep discharge and fast charging capabilities. Further, the power density is relatively superior to PbA and vanadium redox batteries (VRFB), but competitively lower than NiMH and Lithium-ion (Li-ion) counterparts [54].

NaS based battery technology is technically applicable for numerous energy storage applications. Firstly, as this battery have relatively long storage duration they have uniquely capable to support load following services in renewable integration. Similarly, considering 7 hours of storage capability at their rated capacity [30], enables them to follow large scale swings in electric demand throughout

a day; a complementary characteristics well-suited particularly for PV integration. Further, the energy to power ratio is technically favourable as energy reserves to overcome demand-generation mismatch, particularly during forecasting error [55]. The current installation as peaking shifting capabilities and voltage services, proves its technological maturity and effectiveness and in combination to very low contribution towards environmental degradation, this technology provides some of the most pertinent and favorable characteristics required for RES integration, such as load-levelling, uninterruptible power supply (UPS) and back-up emergency power supply. In addition, high temperature enables operation with some high-harsh environmental conditions rodrigues2015modelling.

However, the drawbacks currently, high operational cost and safety concerns pertaining to complex thermal management where the temperature can rise upto 2000°C. In contrast, sodium nickel chloride battery (ZEBRA) technology have a better safety characteristics with lower operational temperature (-40°C to $\sim$ +70°C). However, technical characteristics are not comparatively as favorable compared to NaS or other battery technologies in terms of, specific power and efficiency (even compared to lead-acid batteries) [54].

2.1.4 Lithium-ion Batteries

The properties such as high energy density and very high efficiency (almost 100%) made Lithium-ion (Li-ion) batteries among the most preferred choice, specially in portable electronic devices and electric vehicles where the weight of ESS is prefer-

Table 2.2: Technical characteristics of various types of lithium-ion batteries

	LCO		LMO		NMC		LFP		NCA		LTO	
Cell unit charge (V)	3.0 - 4.2	[28]	3.7	[28]	3.6	[28]	3.2 - 3.3	[28]	3.6	[28]	2.4	[28]
Specific energy (Wh/kg)	150 - 240	[28]	100 - 150	[28]	150 - 220	[28]	90 - 120	[28]	200 - 260	[28]	50 -80	[28]
Specific power (W/Kg)			200	[28]	200	[28]	200	[28]			1000	[28]
Charge rate (C-rate)	0.7 - 1	[28]	0.7 - 1	[28]	0.7 - 1	[28]	1	[28]	0.7	[28]	1 - 5	[28]
Discharge rate (C-rate)	1	[28]	1 - 10	[28]	1 - 2	[28]	1 - 25	[28]	1	[28]	10 - 30	[28]
Cycle life	500 - 1000	[28]	300 - 700	[28]	1000 - 2000	[28]	+2000	[28]	500	[28]	3000 - 7000	[28]
Thermal runaway ($^{\circ}$ C)	150	[28]	250	[28]	210	[28]	270	[28]	150	[28]		
Cost (per kWh)	600	[28]	360	[28]	360	[28]	360	[28]	350	[28]	1005	[28]

ably minimized. Moreover, their use in renewable application is very plausible in the coming decades. Compared to other BESS technologies (e.g. PbA, NiCd, NiMH and ZEBRA), this technology has higher energy density, higher efficiency and longer life cycle and environmental friendliness that makes this technology flexible and feasible in my RES applications [56]. Although 50% of small electronic portable markets, the high cost due to protection required from internal overcharge of the circuit and special packaging and additionally the lifetime are drastically shortened with deep discharging (anything over 80% DoD) and in addition this storage technology is best suited only for application that requires 4 hours of storage, these drastically limits the technology's economical significance in large scale renewable application [57].

Despite this, innovation and development of new types of Li-ion BESS technology is rapid. Table 2.2, summarizes various technical characteristics of commercially available li-ion batteries namely Lithium Iron Phosphate (LFP) Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Nickel Cobalt Aluminum Oxide (NCA), Lithium Titanate (LTO) [58].

LCO is mostly used in portable electronic equipment and is considered the

most promising solution in the field of renewable integration. However, its circuit sensitivity during charge and discharge is highly sensitive, that is, its performance and efficiency is negatively impacted under extreme conditions. In contrast, the performance of LTO batteries is remarkable at extreme temperatures, specially at low temperatures [59]. However, apart from low specific energy its is the costliest among these technologies, hence drastically reducing its economic significance for RES applications [60]. Similarly, LMO batteries being an environmentally suitable candidate for extreme temperature applications and is used in electric vehicles but is not suitable due to its combination of moderate low life cycle and low specific energy. Accordingly, even though LFP batteries has the lowest internal resistance its application is simply not viable considering its low specific energy and comparatively high self-discharge rate than others, nevertheless it is highly utilized in electric vehicles [61]. Therefore, among the Lithium-ion technology the NMC is the best candidate [62]. The potential of NCA battery in vehicular applications is currently very high, due to sufficient energy and power density there are projects for implementation as backup and load-shifting operation in grid-connected renewable applications. The properties of NMC project similar as NCA, however, this technology possess slightly lower energy density than NCA but significantly higher life cycle and as suitable candidate among other technologies for application in the field of RES integration [63].

Table 2.3: Technical characteristics of various flow batteries

	VRFB		Zn-Br		PSB	
Power rating (MW)	0.03-3, 50	[40, 41], [30]	0.05-2	[41]	1-15	[39, 41]
Energy density (Wh/L)	20-70	[42]				
Power density (W/L)	$\sim <2$	[30]	$\sim <25$	[30]	$\sim <2$	[30]
Specific energy (Wh/kg)	10-50	[40, 65]	30-85	[40]	15-30	[39]
Specific power (W/kg)	80-166	[41, 65]	45	[41]		
Power capital cost (\$/kW)	600-1500	[40]	700-2500	[40]	700-2500	[39, 40]
Energy capital cost (\$/kWh)	150-1000	[40]	150-100	[40]	150-100	[40]
Capital cost (/kWh-per-cycle)	5-80	[40]	5-80	[40]	5-80	[40]
Reaction time (ms)	>1000	[42]			20	[30, 66]
Self-discharge rate (% per-day)	small	[41]	small	[41]	small	[41]
Discharge time	sec - 10 hr	[40, 41]	sec-10 hr	[41]	sec-10 hr	[41]
Life cycles	10,000-13,000	[39, 41]	5,000-10,000	[41]	2000-2500	[40, 41]
Lifetimes (years)	10-15	[42]	5-10	[41]	10-15	[41]
Overall Efficiency	0.65-0.85	[40, 41]	0.60 - 0.70	[41]	0.65-0.85	[41]
Temperature operating range ($^{\circ}\text{C}$)	15 - 55	[39]	20 to 50	[66]	20 to 40	[67]

2.1.5 Vanadium-Redox Flow Batteries

The flow batteries have the advantage over other BESS technology types as the energy and power ratings can be independently designed [44] due to its modularity. Accordingly, the structural design, that the energy is stored in external tanks outside the battery, it allows flow batteries to be favourable for long-term storage of energy and power while maintaining high discharge rate. Among various commercialized flow batteries such as polysulfide-bromide (PSB) and zinc-bromide (Zn-Br); VRFB is considered to be technically superior, as shown in Table 2.3.

VRFB are capable to provide various grid services and are competitive to other BESS technologies regarding life cycle, self-discharge rate and response time. Currently, the installations are deployed for energy management services like peak-shifting, voltage support, spinning reserves, emergency UPS, black start mitigation of fluctuating RES power outputs, energy arbitrage. Furthermore, certain key drawbacks such as low energy density is compensated with modularity and the consequent high cost is moderately mitigated with large-scale applications. [64]

2.2 Supercapacitor Energy Storage System

Technical characteristics (Table 2.4) of SCSS are interesting for various RES integration applications that requires reliable high power rating, long life cycle and peak transient power. Currently these characteristics are highly under consideration for commercial deployment of wind and solar energy technologies particularly due to high power density, wide operating temperature range and low internal resistance. The former requiring blade-pitch adjustment that is compensated with high burst of power for optimized LVRT, and the latter requires output power smoothing; that is currently proposed to be achievable through BESS, however they are designed with comparatively higher power rating with detrimental effects on their life cycle [68] and are highly commendable for applications as UPS to critical loads.

Furthermore, in RES integration power electronics plays an important role of interfacing and bridging the RESs to the power grid through DC-DC and or DC-AC links. Commonly used DC capacitors are suitable only for short-term shortage requirement but will require large storage back-up for optimal voltage regulation in case of large-scale applications. The characteristics properties of SCSS are well-suited for such storage requirements with enhanced end-to-end efficiency [69]. In accordance, SCSS serve as a lose-less voltage divider, in comparison to switching regulators with heavy inductors, and effectively supplies load requirements in an event of voltage dip and hence maintain a stable DC link voltage [70]. Nevertheless, SCSS energy density is highly inferior to other energy storage tech-

Table 2.4: Technical characteristics supercapacitor energy storage system

Characteristics	Value	
Power rating (MW)	0 - 0.3	[40, 41]
Energy density (Wh/L)	2 - 10	[40, 42]
Power density (W/L)	100,000+	[40]
Specific energy (Wh/kg)	0.05 - 5	[40]
Specific power (W/kg)	$\sim 100,000$	[40]
Power capital cost (\$/kW)	100-300	[40]
Energy capital cost (\$/kWh)	300 - 2000	[40]
Capital cost (/kWh-per-cycle)	2 - 20	[40]
Reaction time (ms)	<10	[42]
Self-discharge rate (% per-day)	20-40	[39, 40]
Discharge time	ms- 60 min	[40, 41]
Life cycles	50,000	[40, 41]
Lifetimes (years)	10 - 12	[39]
Overall Efficiency	0.75 - 0.83	[42]
Temperature operating range ($^{\circ}\text{C}$)	-40 to 75	[65]

nologies, and to the requirements of RESs integration such as, peak-shifting and storage-durability.

2.3 Battery-Supercapacitors Hybrid Energy Storage System

From previous section it can be summerized that, commonly majority of BESSs have certain drawbacks, for instance, due to low power density they are severely lacking to optimally compensate (economically) transient/abrupt power fluctuations experienced due to load-generation variations. In this case, the lifetime of the BESS are drastically effected [71] leading to recurring replacement or over-sizing of BESS and hence limit it objectivity of application.

One multifarious amalgamation of ESS is that of BESS and super-capacitor

storage systems (SCSS). In this case, the BESS technical characteristics consists of high energy density, low power density, limited life cycle, long reaction time, and relatively lower self-discharge. On the other hand, SCSS have low energy density, high power density, virtually unlimited life cycle, short reaction time, and high self-discharge. Therefore, the resultant HESS exhibits a complementary characteristics between BESS and SCSS, as depicted in Table 2.1 and Table 2.4; and hence provide high energy density, high power density, optimal life cycle and relatively faster dynamic response and at the same time being economically feasible [72–75]. The application of this HESS is commendable in various facets of power network and RESs integration as well as other field of electrical and engineering applications.

2.3.1 Applicative Scope of Battery-Supercapacitor Hybrid Energy Storage System

Several topological investigations and innovations have been explored, based on the connection of BESS and SCSS with numerous configuration of power electronic interface to enhance the HESS integration. Passive, semi-active and fully active topologies and energy management strategies have been presented for providing a degree of control over operation, power allocation, sizing and terminal voltage of BESS and SCSS [76–78].

2.3.2 RESs Output Power and Load Smoothing

The technical characteristics of BESS-SCSS hybrid storage technology is primarily considered for RESs output power smoothing, load side management and large scale commercialized dispatch of RESs, mostly for wind, solar [79–83] and ocean wave energy sources [84, 85]. Further, dependency on accuracy of forecasted values is reduced with increased dispatchability of solar and wind energy resources [86–90]. In this respect, the study in [91], presents a rule-based heuristic power management scheme for dispatching large-scale PV that actively reduces SCSS to one-fifth the size of BESS rating. The same authors in [92], implemented a robust rule-based algorithm to maintain the dispatch-ability of large-scale PV by power fluctuation control under large forecasting error (of 60%). Apart from mitigating the effects of variable output power of RESs power, many complexities of modern power system operation arising due to inherent variability of the load demand specially in grid connected, distant remote areas can be mitigated by this HESS [93–98]. The study in [99], demonstrates the capabilities of HESS for satisfying a decoupled load profile. Further in [100], the capability of HESS to supply peak power requirement is presented. A SVM load predictive energy management system is proposed that predicts load requirements with 100% accuracy with classification time of 0.004866 seconds. Based on this instantaneous predicted load profile it has been observed that the HESS can flexibly satisfy peak load requirement without any delay.

2.3.3 Grid Regulation and Fault Support

Integration of RES into the AC grid introduces many power quality challenges. The sharing of power among grid, RES, and HESS plays a very vital role for a stable across a wide spectrum [101–105]. In [106], a study is presented to highlight the contribution of RES-HESS for mitigating of power imbalance and abrupt frequency variations in a hybrid AC/DC grid. For achieving this, a control algorithm is implemented for generating the reference values for RES, power converters of HESS, and the grid connecting voltage source converter (VSC). As a result, the VSC's switching stress is significantly reduced. Furthermore, the study in [107], demonstrates the contribution of HESS to the inertial response in power systems with high penetration of RES. To demonstrate this, a virtual inertia emulator has been formulated essentially consisting of three-phase inverter and an output LC filter. In combination with the characteristic of HESS, an efficient virtual synchronous generator can be formulated that actively contributes to the inertia of the overall system. The study in [108], exploits the BESS-SCSS HESS characteristics to enhance the primary frequency control (PFC) and the inertial response in a power grid.

In this study, a configuration in which SCSS enhances inertia response and BESS support towards PFC has been presented on a two area system model in which one area is only composed of conventional energy sources and other with increased penetration of RES has been tested. Modelling and sizing of SCSS have been performed based on the rate of change of frequency (RoCoF) whereas BESS is

done to meet the steady-state frequency deviation limit. Accordingly, a fault ride-through control scheme is presented in [109, 110], with BESS for DC link voltage regulation and SCSS supporting large transience in the system. This topology consists of two parallel bidirectional converters, for BESS and SCSS respectively, with the additional inclusion of switches, making it suitable for short-circuit fault tolerant and further proposed the control scheme for the converter is designed as such to reduce the losses due to these additions of switches.

2.3.4 Blackstart of DG Power Grid

In contrast to the complicated restoration process of conventional power systems that is carried out according to predefined guidelines, the whole restoration process is much simpler in case of distributed generation micro-grid, due to the reduced number of controllable variables (micro-sources, loads and switches). However, pertaining to the unpredictability and transience of the micro-sources, they are unsuitable for direct connections to the microgrid. In such cases, different power conversion system (PCS) such as DC/AC, AC/DC/AC converter interface is required. In addition, considering a worst-case scenario in which the fully controllable synchronous generators are absent that would control the voltage, frequency deviations and balance the load and generation conditions of the grid; the operations of the energy source converter interface hence play a key role to emulate a synchronous generator's operational support to allow islanded mode microgrid operation. In these situations, ESS coupled with PCS usually injects active power

into the grid proportional to the frequency deviation. Therefore, the role of ESS is very important in order to maintain the stability of the system as they handle the transient requirement of the system [111], at least during the initial stages of black-start process. In recent studies, HESS has been proved effectiveness during direct start, star delta start, and frequency conversion start conditions and maintain continuous power supply during these conditions, nevertheless on a small-scale system [112].

2.3.5 Regenerative Braking and Electric Vehicles

Conventionally, a practical restriction exists on the quantity and intensity on the application of regenerative braking, as it is impossible to recover its full energy. The extractable amount of regenerative energy depends on many factors such as receptiveness of the energy storage and motor deceleration rate. For a short interval during fast deceleration, the power will be high. This means a significant amount of power is returned to the grid, relative to the power rating of the motor. Hence for capturing maximum energy, the volume of the storing energy should be equal to the change in kinetic energy. This recovered energy remarkably extends the range of EVs. The studies in [113,114], in the context of regenerative energy, investigate various topologies for HESS integration in EV systems and further propose a novel topology that aims to satisfy the peak power demand with a reduced DC-DC converter size. In this proposition, the voltage of SCSS is maintained at a higher value than BESS, with BESS providing power directly only

when SCSS voltage level drops below a preset value, hence smoothing the load profile for BESS. Considering this topology, the capabilities of SCSS effectively utilized in regenerative braking and BESS protection with an improvement in the driving ability of the vehicle at low temperatures.

The experimental research described in [115] investigates the HESS capability for harvesting energy from regenerative braking. It has been observed that hybridization of SCSS with BESS efficiently recuperates high power transfer under regenerative braking and acceleration, and therefore an energy management system (EMS) that can manage power flow to maintain SCSS voltage becomes the key parameter in reducing the overall system losses. In accordance, overall mileage improvement has also been reported in [116], that address the objective to quantitatively minimize both system cost and battery degradation considering the requirement of minimal mileage in EVs. Taking into account a typical city bus driving cycle, non-dominating genetic algorithm is proposed to achieve these objectives for a semi-active topological framework. Therefore, with the objectives achieved at suitable HESS operational temperature (between 15 °C to 40 °C), it has been concluded that a significant increment of 6% increase in the driving range is gained with HESS in comparison to BESS-alone operation

Apart from, efficient harvesting of regenerative braking with potential decrease in the converter size. The integration of SCSS with BESS in EVs subsequently reduces the BESS size and hence the overall EV weight. In study in [117,118], introduces an optimization algorithm potentially to decrease the BESS operational

size by minimization of magnitude and fluctuation of the battery current. This algorithm considers the unpredictability of the load requirement in an EV based on which SCSS reference voltage is regulated which computes a sub-optimal value for the reference current in BESS. Hence an optimal size and increased life expectancy are achieved that is robust in terms of the inaccuracy of future load predictions of EVs. In current studies it has also been postulated that load smoothing achieved with this HESS combination increases lifetime of BESS, the primary energy sources by about 55% with simple power allocation of power between the storage components [119].

2.3.6 Wireless Power Transfer

The sensor nodes of wireless sensor networks are mostly inactive to achieve longer run-times. Conventionally, power being mainly provided by BESS, which is either primary or secondary energy sources. However, considering high resistance of BESS a significant loss occurs due to sleep and leakage current, moreover due to internal BESS impedance a sizable voltage drop is also experienced at the activation instant of the node, limiting the required power to be extracted. Considering these anomalies, in [120], a parallel combination of BESS-SCSS HESS is proposed. Here, with a selection of three BESS, namely silver oxide batteries, lithium batteries and NiMH batteries, it has been observed that hybridization with SCSS is feasible with only the first two as the resistance of NiMH is already optimally low enough. However, for silver oxide and lithium batteries, the combination with a

low resistance SCSS significantly increases the run-time of the sensor nodes with a feasible decrements in leakage current losses.

The properties of HESS have been exploited to enhance the feasibility of wireless power transfer (WPT) applications in EVs [121]. Here the authors proposed a three-mode energy management strategy based on the SoC conditions of HESS components. Hence, in addition, to regulating the energy input from the WPT and manage energy distribution between the BESS-SCSS this study proposes the implementation of a short period of negative current periods in the charging state of the DC-DC converters. This depolarization pulses significantly reduces the stress on the internal resistance of BESS.

A wireless power supply with BESS-SCSS HESS has been developed for powering implantable devices, such as intracranial pressure (ICP) monitors in [122]. The shunt used to drain excess fluid from the brain in hydrocephalus patients fail regularly. Here, the most valuable diagnostic tool is a pressure sensor implanted in the brain. In this respect, WPT based on inductive power transfer technology is implemented on HESS where the HESS powered ICP can meet both the short- and long-term operational requirements, and further the study recorded that SCSS provides a quick charge back up for collection of data.

2.4 Voltage Regulation with Renewable Power

Integration

2.4.1 Voltage Regulation with Hybrid Energy Storage System

The control theory in case of BESS-SCSS hybrid energy storage systems for voltage regulation in a DC grid postulates development of control algorithm and techniques that not only allocates power between BESS and SCSS but also ensures effective response towards voltage deviation experienced at the DC interface of the grid. Thus achieving the objective of storage hybridization and sufficiently harnessing each candidate of the HESS according to their respective dominant complementary characteristics.

In the literature, the control strategy of BESS and SCSS have been presented with several distinctive techniques and control algorithms. The authors in [76,123,124], derived power reference for HESS components using high pass filter (HPF). The sensed high frequency component from the load power is given as reference to the SCSS and further the remaining low frequency component to BESS, thereby separating the frequency components. The power is controlled in a closed loop manner typically using PI controllers.

Similarly, researchers in [125] propose the power allocation strategy between BESS and SCSS based on low pass filter (LPF), postulating a comparatively enhanced and improved performance of the control strategy in comparison to

HPF. Kollimalla *et al.* [126] proposed generation of BESS and SCSS current reference using filter based control strategy. The error signals procured from the DC bus is sent to the PI controller, generating the reference current required for voltage regulation at the DC bus. This current is then split, using LPF into low and high frequency component that serves as a signal generation for switching BESS and SCSS respectively through their corresponding PI controllers. Further, “uncompensated BESS power” due to slow dynamics of BESS is quantified and compensated using terminal voltage ratio between BESS and SCSS. Therefore, SCSS compensates for the transient component of the power flow as well as the uncompensated BESS power.

Pavković *et al.* [127] have designed a filtering scheme based on averaging technique that separates the BESS and SCSS current components. For accelerating the load current response a supplementary “load current feedforward compensator” is introduced. Therefore, the generated signal from the DC bus voltage control loop is combined with the load current feedforward compensator from which the BESS and SCSS reference current signals are then allocated.

Tani *et al.* [128] introduced a polynomial control strategy for SCSS allocation of high frequency fluctuant of wind generators and the load. Here, an algorithm based on LPF extracts the fluctuating current components from the current output of the wind generators and the measured current of the load. Finally, using polynomial estimation functions the required current reference is generated for DC voltage regulation using the value of the inductor voltage derived from the

current components.

All the above mentioned methods meticulously designed for successful application. However, these filter based methodologies have some disadvantages. For instance, power components are not optimally separated by the filters. To obtain optimal splitting of the power components, the filter parameters and the cut-off frequency has to be adjusted distinctively for different loading conditions [129]. Furthermore, implementation of numerous voltage and current sensing devices, combined with slow BESS dynamic response negatively impacts the response of the overall ESS as the control scheme of the SCSS is associated with the control loop of BESS.

Accordingly, Camara *et al.* [130] posits a polynomial based control strategy for DC bus voltage regulation applicable for varying loading conditions and the dynamic system characteristics. Through generation of reference current for BESS and SCSS converters, duty ratios for the converters are derived using control laws. However, additional voltage sensing devices are required for both BESS and SCSS.

Moreno *et al.* [131] propose a power management technique based on neural network for hybrid electric vehicular application. In the test system presented, BESS and SCSS are connected to the DC side and, as an auxiliary storage through DC converter respectively. The SCSS compensates the transient requirement of the drive system. Considering this architectural design the optimized neural algorithm estimates the reference current for SCSS. The results obtained demonstrates a smooth BESS current profile, i.e., BESS compensates for steady state power de-

mand. Nevertheless, several parametric information are required for estimation of reference current, namely the DC bus voltage, vehicle velocity, kinetic energy of the drive system and power flow.

In [132], fuzzy logic based controller is proposed for BESS-SCSS-HESS to regulate the DC bus voltage. With inductor current and the bus voltage as the input to the fuzzy controllers, partial duty cycle for the interfacing converters is derived. The other part of the duty cycle consists of the command generated by maintaining the SoC of SCSS. A desirable characteristics is the decoupled control strategy that enables the flexibility of implementation with reduced number of sensor devices, that in this case, filters and current sensors are obviated that is postulated to improve the response of the storage devices.

2.4.2 Voltage Mitigation with Reactive Capability of PV Inverters

Commonly, the control technique instigated for volt/var management might not be applicable for remote-radial networks, wherein the R/X ratio of the distribution line is non-unity and high [133–135]. As shown in Figure (2.1), due to systematic voltage drop at each bus, the degree of voltage deviation will be very high at the end of a radial distribution network (RDN). Therefore, R/X based quantification is inherently needed. Therefore, the robustness and efficacy of inverter based volt/var management is based on its versatility towards the dynamic change in the distribution grid due to systematic and large scale penetration of RES.

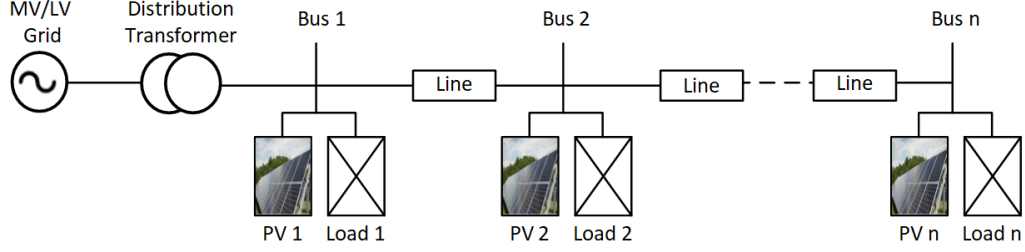


Figure 2.1: Typical radial distribution network.

Several research studies have been presented to quantify and optimally implement the reactive power capability of PV inverters for grid voltage regulation [136–143]. In [136], a local voltage control strategy is proposed based on piecewise linear function. Here, Q-V control curve is defined and implemented locally on the PV inverters and further, a parameter optimization model is built for improving the voltage profile. In [137], a control algorithm is developed for optimal switching of PV inverter. This work proposes a reference power point tracking method for real power curtailment and a voltage controller that regulates the required reactive power.

Accordingly, various converter interface and their stages have been studied [144–148]. The study in [144], presents a single stage conversion system with reactive power control of PV. The proposed converter design achieves both DC-DC and DC-AC conversion in a single stage and can deliver/receive reactive power to/from the grid while continuously delivering active power from PV at maximum power point. Further, a modular multi-level converter for active and reactive power control in grid-connected PV system have been proposed [145]. Here, feasibility analysis for reactive power compensation is derived using voltage

vector space analysis. Thereby enabling the PV system to possess a unidirectional active power and bi-directional reactive power flow. In [146], a local control of active and reactive power for a three-phase single-stage PV inverters is proposed and further, the authors reported that compensation of reactive power through the grid-interactive inverters is simpler and more efficient in comparison to STATCOM.

The study in [149], posits voltage regulation scheme for OLTCs. In this proposition, the proposed control strategy aims to reduce operational stress of the tap changer, shave the utility peak load and decrease the transmission and distribution resistive power losses associated with high PV penetration. In [150], a decentralized control method for voltage rise and line overloads for rural distribution network is presented. Here, both generation curtailment and reactive power control are applied based on voltage and thermal constraints of the system. The methodology is based on sensitivity analysis of the system that obviates the need of direct communication with the DG units and the OLTCs. Nevertheless, this method requires frequent calculations and hence inevitable errors will be present.

Furthermore, a consensus-based distributed algorithm for the reactive power control is presented in [138]. This includes a multi-objective optimization of system power losses, voltage deviation and cost of the reactive power generation, also a utilization ratio for reactive power utilization has been introduced to address different DG capacities. In [139], the authors present two novel reactive power compensation techniques for voltage profile improvement in a low voltage (LV)

network. The first approach is based on linear control scheme while the second implements a non-linear control strategy with the multi-master and master-slave communication approach with the PV inverter respectively.

Furthermore, in rural and urban case scenarios R/X is high as well as the distance between each node is also a contribution towards deterioration of the voltage profile [151]. Considering these parameters various research have been conducted. A reactive power compensation for end feeders in a DG network is proposed in [152]. The control is based on dual-loop robust control strategy, that in combination with optimized parameters, derives a fast and smooth tracking of the load current for obtaining the desired reactive power compensation. Similarly, considering R/X model of RDN and high penetration of rooftop PVs, a coordinated droop-based control strategy [23] has been studied for optimal non-unity power operation of PV inverters for reactive power compensation in urban and rural scenarios (based on different R/X ratios). The study postulates that, PV inverter alone is enough to improve the voltage violation issue in case of urban scenario, however batteries should be integrated locally for economic feasibility.

2.5 Energy Storage Recommendations for Critical Saudi Climatic Conditions

The climatic condition of Saudi Arabia is considered to be extreme, in contrast to typical ambient operational range of most BESS. Over the period of 35 years, the

Kingdom has experienced a warm trend and an increase in temperature extremes both in magnitude and frequency. Today, upto 92% and 89% increase in warm trends have been recorded for day and night conditions respectively. Further, the electric utility of Saudi Arabia aim on bulk integration of RESs in GWs within the next 10 years. For this, VRFB, NiCd, Lead-acid and NaS are applicable for large-scale-utility.

- NiCd is even though applicable but is technically inferior to others based on efficiency, cycle cost and suffers from memory effect.
- Lead-acid batteries have comparatively low life cycle and lacks fast charging capabilities.

In addition, the operating temperature of both NiCd and PbA is less feasible in accordance with the temperature conditions of the Kingdom, and hence additional cooling/protective agents and specialized infrastructure is needed. Therefore, VRBF and NaS energy storage technologies are recommended for application as energy storage requirements in Saudi Arabia, specifically as long-term seasonal energy storage systems. Both these technologies are technically competitive, however, the due to lower cycle cost and comparatively very high life cycle, VRBF is recommended as the most promising technology in scale of utility grade, large-scale application.

CHAPTER 3

DC BUS VOLTAGE REGULATION WITH HYBRID BATTERY- SUPERCAPACITORS

Overview: In a DC microgrid, the DC bus plays an important role of maintaining optimal flow between the generation, loads and the energy storage systems. A control strategy for batteries and supercapacitors based on k - Type compensators and a nonlinear PI controller (NPIC) respectively. The formulated control design is tested for voltage regulation in a standalone microgrid. Furthermore, a comparative analysis is presented with benchmark LPF based controller.

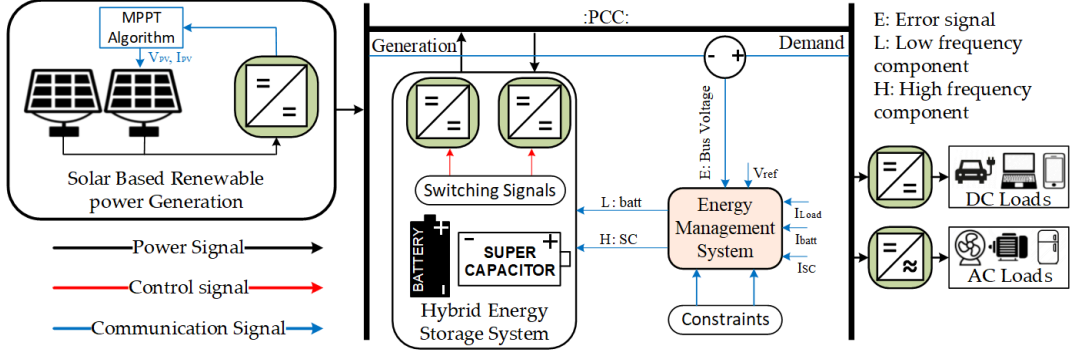


Figure 3.1: Block diagram of microgrid system integrated with battery-supercapacitor hybrid storage energy storage system.

3.1 Problem Description

Voltage regulation is an important parametric aspect for increasing solar PV penetration in a power network. Considering the architecture of the microgrid as shown in Figure 3.1, the principle of HESS is compartmentalization and allocation of unpredictable RES and load power variations in a grid network. Therefore, slow or average power demand are suitable for BESS and fast or peak transient power requirements are compensated by SCSS. To achieve this, an optimal power allocation and acceptable HESS operation is imperative.

In the classical strategy [153], disturbances due to variation of demand-generation is divided into high frequency (I_{HFC}) and low frequency power (I_{LFC}) component based on the total error signal (I_{t-ref}) generated at the DC bus terminal by comparing the deviation of the DC link voltage (V_{dc}) and the desired reference voltage (V_{ref}). These form the respective reference current for the components of the HESS (3.1)-(3.3). The power filtration is done using [154]:

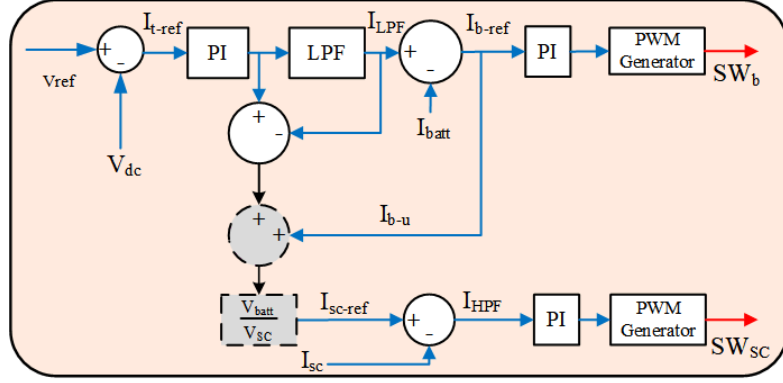


Figure 3.2: LPF based interconnected power allocation between BESS and SCSS.

$$\tau_{lpf}(s) = \frac{2\pi f_{lpf}}{s + 2\pi f_{lpf}} \quad (3.1)$$

where, f_{lpf} is the filter cut-off frequency that can be calculated with numerous different methods; as a function of sampling frequency (f_s) of RES [155–158], iterative examinations [159, 160], ragone plots [161, 162] or by adaptive studies [163–165].

$$I_{LFC} = \tau_{lpf} \cdot (I_{t-ref}) \quad (3.2)$$

$$I_{HFC} = I_{t-ref} - I_{LFC} \quad (3.3)$$

The formulated low frequency component provides the reference current of BESS (3.4). This is compared with the actual BESS current (I_{batt}). Accordingly, the PWM generator provides the required switching through SW_b corresponding to the duty ratios generated by the PI controller. In similar terms, the reference

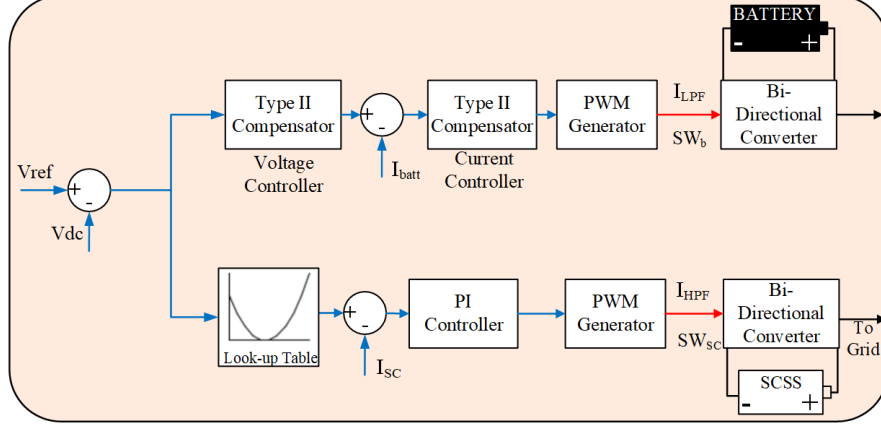


Figure 3.3: Proposed controller design for power management between BESS and SCSS.

current for SCSS (I_{SC-ref}) is formulated, by comparing with the actual SCSS current (I_{sc}), for generating the required switching of SW_{SC} , as shown in Figure 3.2.

$$I_{b-ref} = I_{LFC} \quad (3.4)$$

Nevertheless, owing to the slow dynamic response of the BESS, I_{batt} may not instantly coordinate with I_{b-ref} . Resulting in a fraction of power in (I_{LFC}) that remains uncompensated (I_{b-u}). This requires an additional power sharing ratio between BESS and SCSS is needed [126, 166] and additional voltage sensing devices. Therefore, the complexity of LPF strategy is increased that requires formulation and design of an optimal power sharing technique that optimally switches SCSS to limit its operation to facilitate power compensation (short-term transient variation) rather than energy compensation (long-term average variation) in the system [167].

3.2 Proposed HESS Control Strategy

The BESS being a dispatchable energy source can be charged or discharged with the grid requirements in terms of excess/deficit power. The BESS is controlled with an outer and an inner voltage and current control loops respectively and hence operated in voltage controlled mode for DC bus voltage regulation as shown in Figure 3.3.

For procuring a suitable BESS response towards voltage regulation considering the technical power density limitations of BESS a type II controller is designed for the voltage and current feedback loops. Type II controllers, are a type of lead compensators that facilitate enhanced and robust performance for grid regulation operations. The combination of poles and zeroes provide appropriate shaping of the control loops. This is achieved through modification of the phase and gain characteristics of open-loop frequency response. Providing a compensation from 0° upto 90° a zero steady state error can be achieved with faster response and nominal overshoot through appropriate tuning. The controller transfer function, magnitude transfer function and argument is given in equations (3.5)-(3.7)

$$\begin{aligned} H_T(s) &= \frac{\left(1 + \frac{s}{w_z}\right)}{\left(\frac{s}{w_{po}}\right)\left(1 + \frac{s}{w_p}\right)} \\ &= \frac{w_{po}}{w_z} \left(\frac{1 + \frac{w_z}{s}}{1 + \frac{s}{w_p}} \right) \\ &= v \left(\frac{1 + \frac{w_z}{s}}{1 + \frac{s}{w_p}} \right) \end{aligned} \tag{3.5}$$

$$H_T(jw) = \frac{|1 + \frac{jw}{w_z}|}{|\frac{jw}{w_{po}}| |1 + \frac{jw}{w_p}|} \quad (3.6)$$

$$\arg H_T(jw) = \tan^{-1}\left(\frac{w}{w_z}\right) - \tan^{-1}\left(\frac{w}{w_p}\right) - \frac{\pi}{2} \quad (3.7)$$

where, w_z and w_p are the poles and zeros of the controller in the frequency domain respectively and v is the required value of the gain. Accordingly, k-factor approach is used to design these controller, that allows to shape the controller with a desired output based on loop cross-over frequency and phase margin, based on the equation in (3.8)-(3.10)

$$k = \tan\left(\frac{\text{phase boost}}{2} + \frac{\pi}{4}\right) \quad (3.8)$$

$$f_p = k.f_c = \tan\left(\frac{\text{phase boost}}{2} + \frac{\pi}{4}\right)f_c \quad (3.9)$$

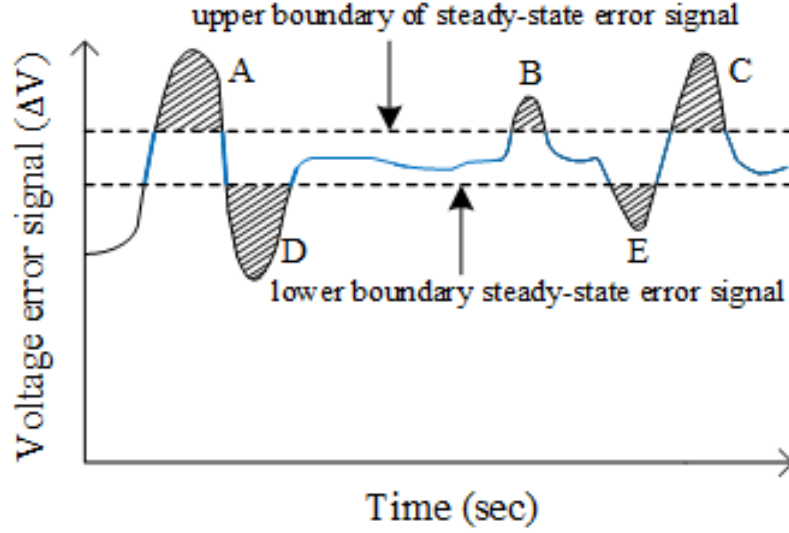


Figure 3.4: Allocation of power between BESS and SCSS based on voltage deviation at the DC bus.

$$f_z = \frac{f_c}{k} = \frac{f_c}{\tan(\frac{\text{phase boost}}{2} + \frac{\pi}{4})} \quad (3.10)$$

Therefore, the stability and response of BESS is acquired by designing the voltage and current control loops using k-factor approach and low bandwidth is considered in designing these controllers, correlative to the slow dynamic response of BESS during generation and or load variations. So, BESS compensates only the average long-term power demand of the system with a smooth transition and hence contribute to the prolonged life of BESS, due to reduction in current level.

Accordingly, with BESS being controlled to provide a constant steady state voltage support to the DC bus (as shown by the blue lines in Figure 3.4) the operation of SCSS can be designed to utilize them corresponding to their domi-

nant operational characteristics. Firstly, considering low energy density of SCSS, their operation during steady state voltage deviation will negatively effect SCSS lifetime and technological significance. So, SCSS operation should rapidly acquire zero value when bus voltage has been reduced from a transient to a steady state requirement as depicted in Figure 3.4. Secondly, a fast dynamic response is needed for abrupt power variations.

Therefore, to establish this non-linear function and to limit the SCSS operation during steady state voltage deviation, we formulate non-linear PI controller design that is driven through a 1-D Look-up table (LUT) as shown in Figure 3.3. The main objective of this strategy is the identification of two tolerable boundaries, lower and upper boundary of the DC bus voltage as shown in Figure 3.4. Hence, based on the observations on the generated error signals by V_{ref} and V_{dc} at the DC link, the controller is set to operationally obviate SCSS towards regulating the under-voltage and over-voltage conditions hence limiting its power absorption and injection respectively and correspondingly defining its lower and upper boundary limits. In this way, the SCSS controller will be limited and not operate within the steady state region, that is compensated by BESS. During the dynamic load changing process the SCSS is charged in regions A, B and C to regulate the voltage below the upper boundary region and absorb the redundant energy. Similarly, in regions D and E voltage is regulated above the lower boundary region by instantaneous discharging of SCSS and supplying the deficient power requirement. Additionally, this strategy allows restriction of power transition during steady

state errors through required suitable model based regression techniques. The operational dynamics are further defined in Section 3.3.

3.3 Design Framework of the Microgrid

Figure 3.1 illustrates the architecture of the DC microgrid under consideration in this study.

3.3.1 Modelling and Configuration of PV Power Generation System

Majority of relevant research studies [168, 169], rely on the representation of the PV cell module as an electrical equivalent of single diode-five parameter circuit, primarily due to its sufficient accuracy and simplified resilience to fit experimental data. In lieu, adoption of double diode seven parameter model [170] is inherently complicated without any considerable gain in accuracy. Accordingly, other approaches have been proposed, for instance [171], employs the Gompertz function for PV representation.

The single-diode five parameter model in this study includes a photocurrent source with series resistance, shunt resistance and a diode. Further, the generated photocurrent, I_{ph} , ideality factor of the diode, μ , shunt resistance, R_{sh} , series resistance, R_s and the saturation current, I_{sat} are the five parametric estimation values of the model. Albeit for simplicity, some studies neglect R_{sh} [172, 173] or both R_{sh} and R_s [174].

The implicit and explicit form of the equation are as follows [175]:

$$I_{pv} = I_{ph} - I_{sat} \left[\exp\left(\frac{V_{pv} + R_s I_{pv}}{\mu V_{th}}\right) - 1 \right] - \frac{V_{pv} + R_s I_{pv}}{R_{sh}} \quad (3.11)$$

$$V_{th} = \frac{n_s k_B T}{q} \quad (3.12)$$

where V_{th} is the array thermal voltage represented with its relation to μ , series connected cells (n_s), Boltzmann constant (k_B), electron charge (q) and the p-n junction temperature of the diode (T). The μ range is selected as $1 \leq \mu \leq 1.5$. The relationship of the generated photocurrent to the PV cell current and the solar irradiance is represented as:

$$I_{ph} = (I_{ph,n} + I_{tsh} \Delta T) \frac{\Psi}{\Psi_n} \quad (3.13)$$

where $I_{ph,n}$ implies the photocurrent at standard test conditions (i.e. 25° C and 1000 W/m²); I_{tsh} is the current/temperature coefficient; ΔT , in Kelvin, is the difference between the actual temperature and the nominal temperature; Ψ and Ψ_n are the irradiation on the device and the nominal irradiation respectively in W/m².

Furthermore, $I_{ph,n}$ can be formulated by (3.14)

$$I_{pv,n} = \frac{R_{sh} + R_s}{R_{sh}} I_{sat} \quad (3.14)$$

Table 3.1: PV panel parameters at standard condition

Description		Value
Power at maximum power point	(P_{MPP})	200 W (-5% \ +10%)
Voltage at maximum power point	(V_{MPP})	26.30 V
Current at maximum power point	(I_{MPP})	7.61 A
Open circuit voltage	(V_{OC})	32.90 V
Short circuit current	(I_{SC})	8.21 A

The standard parameters of the structured PV panel is shown in Table 3.1 that is utilized to obtain the I-V characteristics for varying irradiance with constant temperature and varying temperature with a constant irradiance and the corresponding values are utilized for proving the validity of the design model in accordance with the standardized design of Kyocera KC200GT PV array.

Further, with the perturbation of the operating voltage to ensure maximum power, the perturb and observe method for maximum power point tracking (MPPT) is integrated to the PCC of the DC grid through a boost converter.

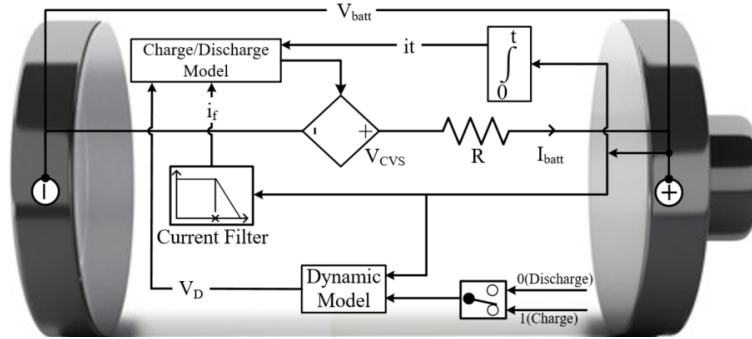


Figure 3.5: Equivalent circuit model of PbAc-BESS.

3.3.2 Modelling of Battery

The equivalent circuit of Lead-acid (PbAc) BESS is shown in Figure 3.5. This model accurately represents the operation of BESS voltage (V_{batt}), consisting of controlled voltage source (V_{cvs}), internal resistance (R_b), charge and discharge model and a non-linear dynamic design of BESS based on its hysteresis phenomenon.

The battery voltage is calculated as given in (3.15) considering the polarization constant (ρ_b), exponential zone voltage (α) and the exponential capacity(β).

$$V_{batt} = E_b - \frac{\rho_b \Gamma_b}{\Gamma_b - it} \cdot it - R \cdot i_{batt} + \alpha e^{(-\beta \cdot it)} - \frac{\rho_b \Gamma_b}{\Gamma_b - it} \cdot i_f \quad (3.15)$$

where Γ_b is the maximum capacity of the BESS and "it" represents the actual extracted BESS charge. The filtered current (i_f) establishes the particularity of the model, exhibiting moderate voltage dynamics corresponding to current step response, inherently also solving the problem associated with the algebraic loop that requires electrical systems [176].

$$R_\rho = \rho_b \frac{\Gamma_b}{it} \quad (3.16)$$

$$R_\rho = \rho_b \frac{\Gamma_b}{it - 0.1 \cdot \Gamma_b} \quad (3.17)$$

The non-linear variation of open circuit voltage of BESS with the SoC is modeled using the polarization resistance (ρ_b). Generally, the polarization resistance is

designed according to equation (3.16). However, in case of fully charge BESS (i.e. $it = 0$), the value of this resistance will be impractical [177]. Therefore, in relation to the experimental results, the evaluated polarization resistance contribution is about 10% to that of BESS capacity [178,179]. Also, the rapid voltage increase as the BESS reaches full charge is also covered by this modelling methodology and hence represented by equation (3.17).

$$\frac{V_D(s)}{B_M(s)} = \frac{\alpha}{1/(\beta \cdot i_{\text{batt}}(t) \cdot s + 1)} \quad (3.18)$$

Irrespective to the SoC of BESS, there exists a hysteresis phenomenon only in the exponential area between the SoC and the charge/discharge process [180]. This phenomenon is quantified using the dynamic model of BESS based on equation (3.18). Inclusive of the formulated dynamic zone voltage (V_D) and the BESS charge/discharge mode (B_M), the developed model of charge and discharge characteristics is obtained as given in (3.19)-(3.20), [181].

$$V_{\text{ch}} = E_b - \rho_b \cdot \frac{\Gamma_b}{it + 0.1 + \Gamma_b} \cdot i_f - \rho_b \cdot \frac{\Gamma_b}{\Gamma_b - it} \cdot it + \mathcal{L}^{-1} \left[\frac{V_D(s)}{B_M(s)} \cdot \frac{1}{s} \right] \quad (3.19)$$

$$V_{\text{dch}} = E_b - \rho_b \cdot \frac{\Gamma_b}{\Gamma_b - it} \cdot i_f - \rho_b \cdot \frac{\Gamma_b}{\Gamma_b - it} \cdot it + \mathcal{L}^{-1} \left[\frac{V_D(s)}{B_M(s)} \cdot 0 \right] \quad (3.20)$$

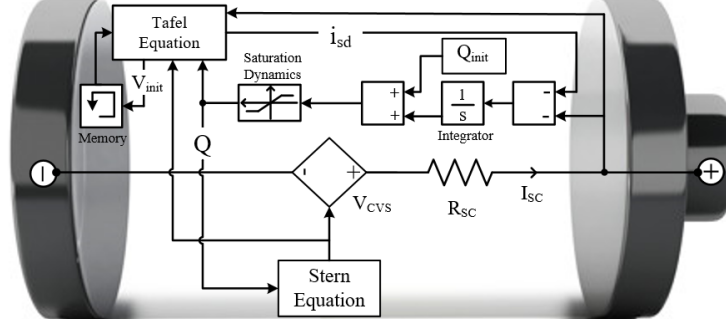


Figure 3.6: Dynamic model of SCSS.

3.3.3 Modelling of Supercapacitor

An SCSS is an electrochemical capacitor consisting two electrodes that allows the application of potential across its cell; double layers are hence present at each electrode-electrolyte interface. In this study a non-linear stern-tafel mathematical model is used that gives the relationship between current, voltage and availability of charge during the charge/discharge process [182].

The terminal SCSS current (I_{sc}) is the input to the dynamic model and the output comprises of the corresponding voltage (V_{sc}) and SoC value. A detailed dynamic model is depicted in Figure 3.6

$$\Gamma_{sc} = \Gamma_{si} + \int_0^t -(i(t) + i_{sd}(t))dt \quad (3.21)$$

The electric charge of SCSS (Γ_{sc}) is quantified by equation (3.21), using the initial charge amount (Γ_{si}), series current (i_{sc}) and the self-discharge current (i_{sd}). The function of saturation limit helps to prevent overcharge or over-discharge by restricting the calculated amount of charge within a specified range.

$$\frac{1}{C} = \frac{1}{C_M} + \frac{1}{C_G} \left(1 + \frac{\delta\sigma_A}{\delta\sigma} \right) \quad (3.22)$$

$$i_{sd}(t) = -A \cdot i_d \cdot N_L \cdot \exp \left\{ \frac{C_T \cdot F}{G \cdot T_s} \cdot \left(\frac{V_{sc}}{N_s} - \frac{V_{smax}}{N_s} - \Delta V_s \right) \right\} \quad (3.23)$$

$$V_{scv} = \frac{N_L \cdot N_s \cdot \Gamma_{sc} \cdot r_m}{N_p \cdot N_L^2 \cdot \epsilon_p \cdot A} + \frac{2 \cdot N_L \cdot N_s \cdot G \cdot T_s}{F} \cdot C_T \cdot r_m \cdot \sinh \left(\frac{\Gamma_{sc}}{N_p \cdot N_L^2 \cdot A \sqrt{8 \cdot G \cdot T_s \cdot \epsilon_p \cdot m_c}} \right) \quad (3.24)$$

The Tafel equation [183] is a generalized plot which has several different applications, in this study it used to generate the leakage current (I_{sd}) waveform of the SCSS. Based on the modified value of capacitance with the inclusion of the surface charge of ions and the charge density, an accurate ion alignment can be portrayed using the Stern equation. This improved capacitive summation is shown in equation (3.22). Considering this additional improvement, the voltage form of combined Stern-Tafel model is computed using equation (3.24). For modelling the SCSS current, the voltage form formulated is substituted in the Tafel equation (3.23), where F and G are the Faraday and ideal gas constant respectively.

Hence the curve obtained can be implemented across academic fields for various curve modelling practices. In this study, the SCSS current is modeled with this curve while the ideal gas constant, temperature ratio and over-potential is to

vary the exponent of the curve [183]. Accordingly, using equation (3.22) the Gouy-Chapman model [184] is further improved with the inclusion of the influence of the motion of the thermal ions on the capacitance. From these values, the rest of the parameters such as, ion alignment factor, model capacitance (C_M), thermal motion capacitance (C_G), molecular radius (r_m), molar concentration (r_c), material permittivity (ϵ_p), operating temperature (T_s), over-potential (ΔV_s), number of parallel and series SCSS cells (N_p , N_s), number of electrolyte layers of SCSS (N_L) and the inter-facial area between the electrode-electrolyte (A) are used to define the combined Stern-Tafel model of SCSS.

3.3.4 Modelling of Bi-directional DC-DC Power Converters

Using small signal analysis, the open-loop transfer function of the bi-directional converter is derived [185–189]. The ratio of inductor current to duty cycle (3.25) and ratio of voltage output to duty ratio (3.26) are used for modelling:

$$G_{id} = \frac{\frac{V_{in}}{1-D}(2 + sR_L)}{(1 - D)^2 R_L + sL + s^2 R_L C} \quad (3.25)$$

$$G_{vd} = \frac{\frac{V_{in}}{R_L(1-D)^2}(R_L^2(1 - D)^2 - sR_L)}{(1 - D)^2 R_L + sL + s^2 R_L C} \quad (3.26)$$

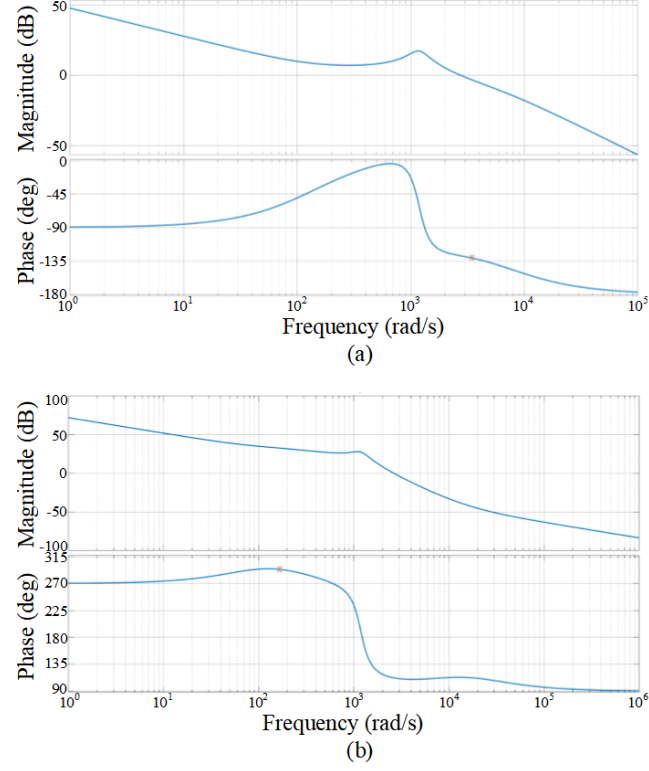


Figure 3.7: Bode plot of BESS controller: (a) Current loop (b) Voltage loop.

where, V_{in} is the input voltage, R_L is the load resistance, C is the output capacitance of the converter, L is the inductance of the converter and D is the duty ratio of the converter.

The inductor current to duty ratio and output voltage to duty ratio small signal transfer functions are derived as:

$$G_{id} = \frac{190230.4(s + 130)}{(s^2 + 432s + 1412760.4)} \quad (3.27)$$

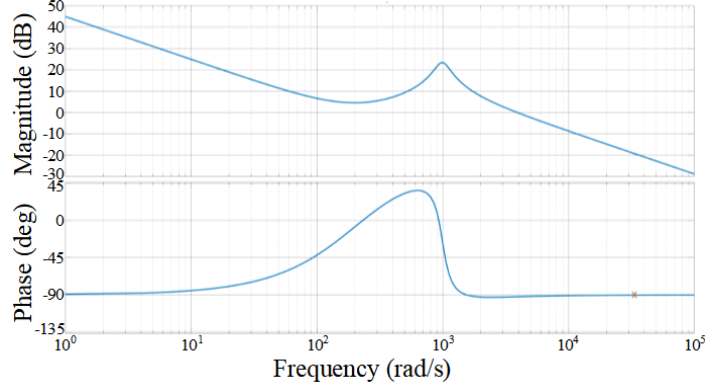


Figure 3.8: Bode plot of current control loop of SCSS.

$$G_{vd} = \frac{-0.369(s^2 - 11068s - 212703645)}{(s^2 + 432s + 1412760.4)} \quad (3.28)$$

Further, the inductor current to duty ratio small signal transfer function is derived as:

$$G_{id} = \frac{73166.1(s + 235.9)}{(s^2 + 259.5s + 9897944.2)} \quad (3.29)$$

Accordingly, the bandwidth for the k- type compensator for BESS controllers are kept small so as to emulate slow dynamic response of BESS. The current controller bandwidth is set to $f_{sw}/67$ of the switching frequency (f_{sw}), with a desired phase margin of 52° . Accordingly, the voltage controller is set to $f_{sw}/1380$. In this study the switching frequency is set to 30kHz. The transfer function of the derived current controller T_i and the voltage controller T_v are derived as follows:

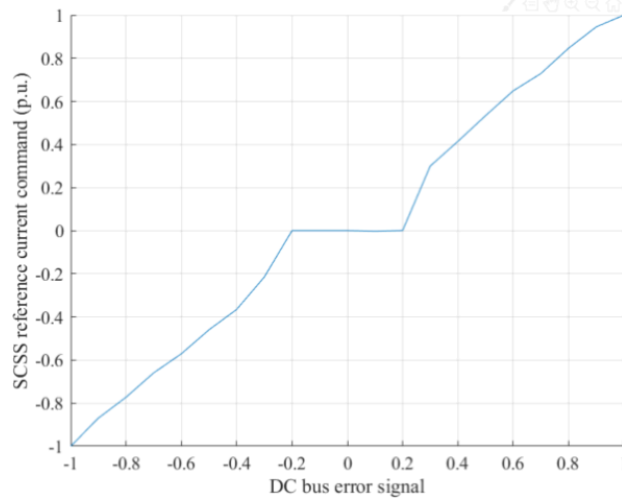


Figure 3.9: Graphical representation of the input and the output relationship formulated in the LUT - SCSS controller loop.

$$T_i = \frac{78.7(s + 1179.8)}{s(s + 6511)} \quad (3.30)$$

$$T_v = \frac{180.9(s + 83.8)}{s(s + 220)} \quad (3.31)$$

The bode plots the current and voltage control loops are shown on Figure 3.7 (a) and (b) respectively.

In case of SCSS, a PI controller is developed to control the generated input current from the boost converter. The general transfer function is represented by (3.32). The proportional gain constant (k_p) is set to 0.05 and integral gain (k_i) is taken as 10. Hence, the a phase margin of the PI controller obtained is 87.7° and

a bandwidth of 3914 rad/sec. Figure 3.8 represents the resultant bode plot of the inner current loop and the PI controller of the SCSS converter.

$$T_{PI} = \frac{k_p s + k_i}{s} \quad (3.32)$$

The voltage error at the DC bus is taken as the input to the LUT controller. The input signal is limited between -1 to 1 range. The generated output voltage is limited between the range of -3V to 3V (in this study), that serves as the input signal to the LUT controller by reduction and normalization to $1/3^{rd}$ of its value. The signal is amplified to boost the transient power compensation by multiplying the signal with the base value of the current hence generating the nominal value of SCSS reference current.

The SCSS controller is developed based on the subjective model based requirement of SCSS and the microgrid. The graph shown in Figure 3.9 depicts the relationship between the input of LUT controller, as voltage error of the DC link, and the generated SCSS current reference output to the LUT controller. This output is selected to remain during steady state error conditions, between -0.2 to 0.2 p.u., and hence create a zero reference current for SCSS when the DC voltage error is low. Accordingly, the above these values the output of the controller increases that is set non-linearly in accordance to the operational requirement deemed to be required for rapid voltage regulation of the DC link voltage.

3.4 Result and Discussion

The proposed control strategy is analyzed and compared with LPF control strategy in a DC microgrid system with standalone 480 W - PV power source with a desired reference voltage level (V_{ref}) of 48 V. The nominal parameters of the system are given in Table 3.2 The analysis is performed for various load-generation variations in the microgrid. Corresponding to this, the regulation of DC bus magnitude and its degree of deviations are compared to mark the robustness of the proposed control strategy. In addition, comparison is also presented between the BESS SoC for quantifying the efficacy of the proposed controller towards reduction of BESS stress current and the subsequent increase in life cycle.

3.4.1 Increment in Load Demand

In this case, the load resistance is originally set to $R_L = 4.8 \Omega$, that projects a load requirement of 10 A and the solar PV panel operates at an irradiance, $S = 509 \text{ W/m}^2$, with temperature, $T = 25^\circ\text{C}$. The resultant generated power (P_{spv}) is 480 W at MPPT. At this initial stage, the DC bus voltage (V_{dc}) operates at 48 V.

Table 3.2: Converter parameters of battery and supercapacitor

Components	Ratings
Battery (BESS)	24 V, 14 Ah
Supercapacitor (SCSS)	32 V, 29 F
Inductance of BESS converter	230 H
Output capacitance of BESS converter	2000 F
Inductance of SCSS converter	600 H
Output capacitance of SCSS converter	1000 F
Inductor parasitic resistance	0.1 Ω
Capacitor equivalent series resistance	0.1 Ω

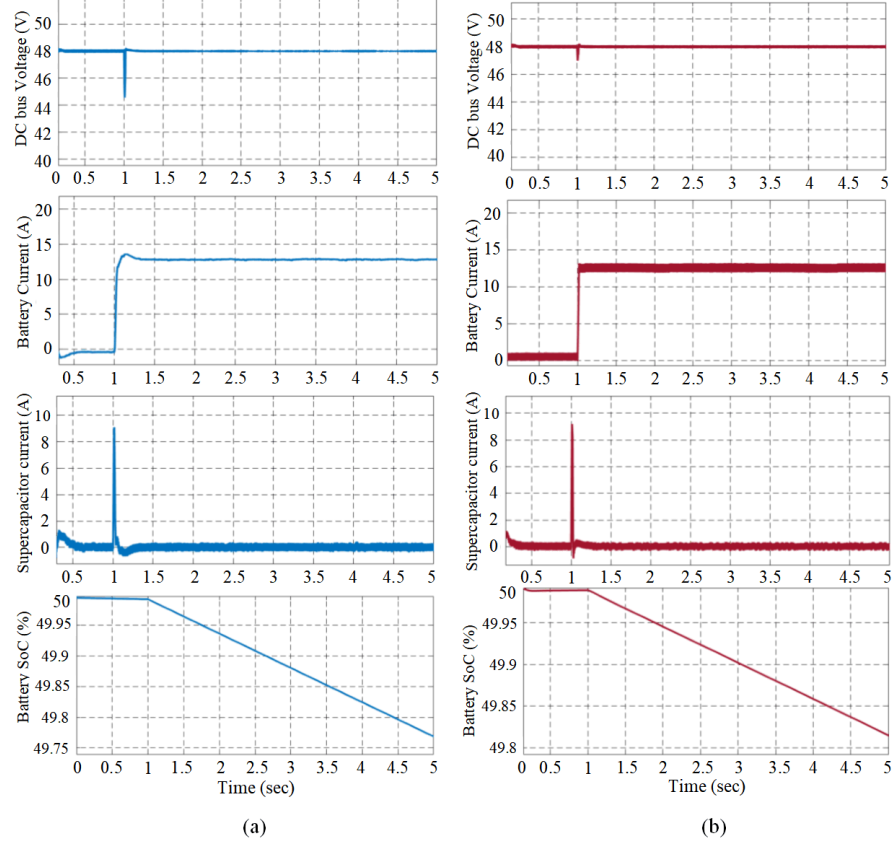


Figure 3.10: Results obtained with abrupt load increase in microgrid. a) LPF control strategy; b) proposed strategy.

During the operational period, $t = 0.1$ sec an abrupt step increase in load demand from 10 A to 16.25 A is experienced by decreasing R_L to 2.95Ω . Therefore, V_{dc} drops is experienced at this instant and to maintain the voltage at 48 V the surplus load demand needs to be supplied by the HESS.

In the LPF control strategy, the BESS compensates the average power difference (300 W) experienced due to the load increment and reaches a steady state discharge current of 12.5 A at $t = 1.25$ sec with an initial overshoot as shown in Figure 3.10 (a). Accordingly, SCSS compensates for the short-term high frequency transient component to maintain the voltage at 48 V through a short-term

current discharge.

In the proposed strategy, the BESS reaches a steady state current at of 12.5 A $t = 1$ sec with negligible duration of the current overshoot, as shown in Figure 3.10 (b). Similarly, SCSS compensates for the short-term transient power mismatch and switches to a steady state comparatively faster than the LPF strategy.

The efficacy based comparison between these two methods is firstly done on the basis of voltage magnitude and its degree of deviation at the DC bus (V_{dc}). As observed in Figure 3.10 (a)-(b), the LPF strategy is unable to optimally regulate V_{dc} during transient conditions and the voltage drop experienced drops down to 44 V, whereas in the proposed method it is 47 V. This is mainly due to the slow dynamics of BESS, explained in Section 3.1 that not only contributes to the voltage deviation and magnitude but also negatively impact BESS lifetime. Secondly, the impact on the BESS % SoC decrease in the proposed method is lower as compared to the LPF method at the end of the operational analysis.

3.4.2 Decrement in Load Demand

In this case, the solar PV panel operates at $S = 509 \text{ W/m}^2$ and $T = 25^\circ\text{C}$. The resultant generated P_{spv} is 480 W at MPPT and initially R_L is set at 4.8Ω , that projects a load requirement of 10 A. At this initial stage, V_{dc} operates at 48 V. During the operational period, $t = 0.1$ sec an abrupt step decrease in load demand from 10 A to 5 A is experienced by increasing R_L to 9.6Ω . Therefore, a rise in V_{dc} is experienced at this instant and to maintain the voltage at 48 V the surplus

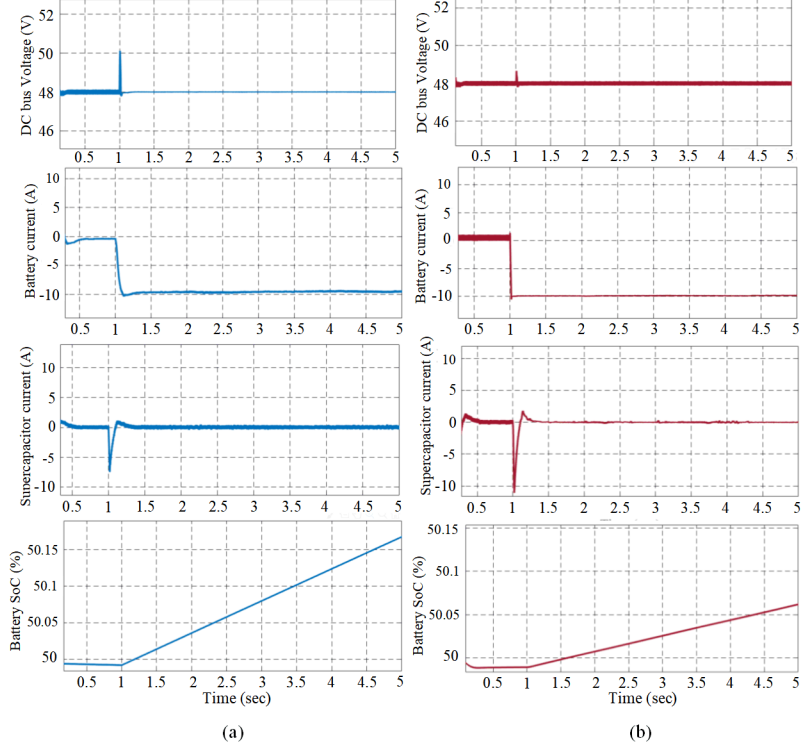


Figure 3.11: Results obtained with abrupt load decrease in microgrid. a) LPF control strategy; b) proposed strategy.

generation needs to be absorbed by the HESS components by charging them.

In the LPF control strategy, the BESS compensates the average power difference (240 W) experienced due to the decrease in load demand and reaches a steady state charge current of 10 A at $t = 1.15$ sec with and initial current overshoot as shown in Figure 3.11 (a). Accordingly, SCSS compensates for the short-term high frequency component to regulate the DC bus voltage.

In the proposed strategy, the BESS reaches a steady state charge current at of 10 A $t = 1$ sec with negligible duration of the current overshoot, as shown in Figure 3.11 (b). Similarly, SCSS compensates for the short-term transient power mismatch to regulate V_{dc} at 48 V through short-term current charge of 7.5 A and

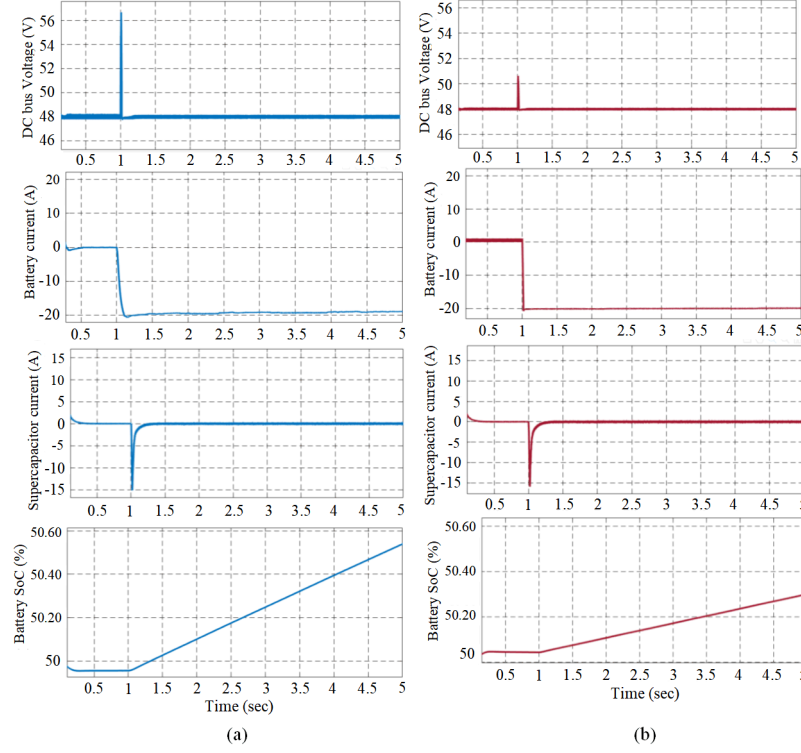


Figure 3.12: Results obtained with abrupt increase in solar PV generation in microgrid. a) LPF control strategy; b) proposed strategy.

switches to a steady state comparatively faster than the LPF strategy.

The efficacy based comparison between these two methods is firstly done on the basis of voltage magnitude and its degree of deviation at the DC bus (V_{dc}). As observed in Figure 3.11 (a)-(b), the LPF strategy is unable to optimally regulate V_{dc} during transient conditions and the voltage rise experienced reaches upto 50 V, whereas in the proposed method it is 48.5 V. This is mainly due to the slow dynamics of BESS, that attributes uncompensated current leading to this additional voltage deviation and magnitude and inclusively negatively impact BESS lifetime. Secondly, the impact on the BESS % SoC increase in the proposed method is less as compared to the LPF method at the end of the operational analysis.

3.4.3 Increment in Solar PV Generation

In this case, the load resistance set to a constant $R_L = 4.8 \Omega$ during the entire operational analysis, that projects a load requirement of 10 A. The solar PV panel initially receives, $S = 509 \text{ W/m}^2$, with constant temperature, $T = 25^\circ\text{C}$. During the operational period, $t = 1 \text{ sec}$ the irradiance is abruptly increased to 990 W/m^2 . The resultant generated power (P_{spv}) is therefore increase from 480 W to 960 W in the MPPT mode. A load-generation mismatch occurs at this interval with surplus of 480 W/m^2 generated from the PV. Accordingly, the impact on the DC bus voltage is experienced in the form of voltage rise which is required to be regulated by the redirecting this surplus power generation and charging the HESS.

In the LPF control strategy, the BESS absorbs the surplus power generated by charging and compensating for the average power requirement of the system and reaches a steady state current of 20 A at $t = 1.25 \text{ sec}$ with an initial overshoot as shown in Figure 3.12 (a). In the proposed strategy, the BESS current comparatively reaches a steady state faster instantly at $t = 1 \text{ sec}$ with negligible duration of the current overshoot, as shown in Figure 3.12 (b). The SCSS compensates for the short-term transient power mismatch by charging at 15 A and switching off to a steady state comparatively faster than the LPF strategy.

The efficacy based comparison between these two methods is firstly done on the basis of voltage magnitude and its degree of deviation at the DC bus (V_{dc}). As observed in Figure 3.12 (a)-(b), the LPF strategy is unable to optimally regulate

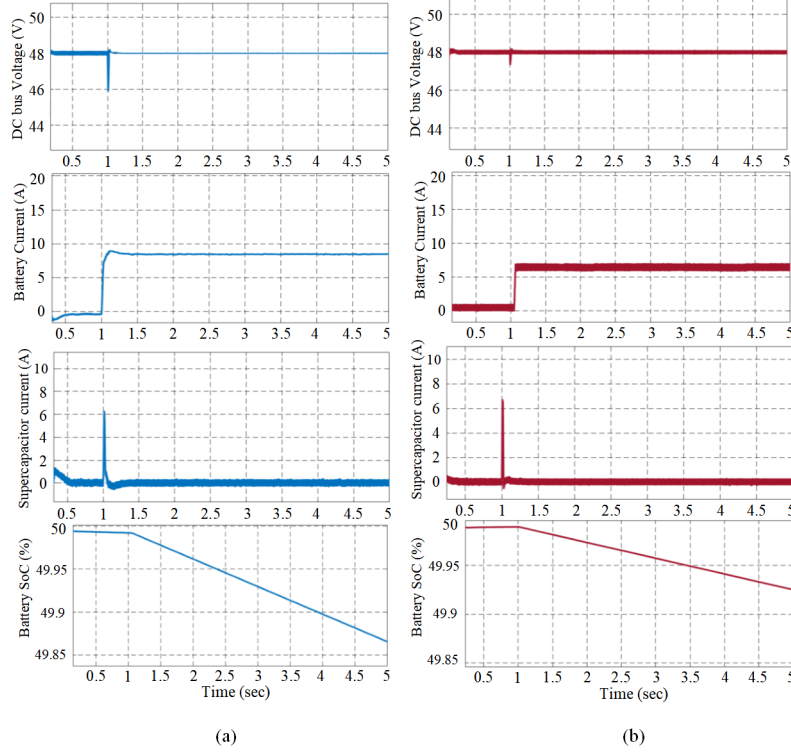


Figure 3.13: Results obtained with abrupt decrease in solar PV generation in microgrid. a) LPF control strategy; b) proposed strategy.

V_{dc} during transient conditions and the voltage rise experienced goes upto to 56 V, whereas in the proposed method it reaches 50 V. This is mainly due to the slow dynamics of BESS that results in a fraction uncompensated current that attributes towards the observed voltage deviation and its respective magnitude. Secondly, the impact on the BESS % SoC increase in the proposed method is less as compared to the LPF method at the end of the operational analysis.

3.4.4 Decrement in Solar PV Generation

In this scenario, initially the irradiance to the solar arrays is 509 W/m^2 and R_L is kept constant during the whole operational span at 4.8Ω with a current demand

at 10 A. During the $t = 1$ sec of the operational period, the irradiance to the solar panels is abruptly decreased to 300 W/m^2 and the power generated by the PV decreases from 480 W to 280 W in the MPPT mode. The initial voltage maintained at 48 V at the DC bus therefore, experience a voltage drop at $t = 1$ sec and hence requires an intervention for voltage regulation that is provided by the discharging of the HESS to overcome the deficient power supply to the load.

In the LPF control strategy, the BESS compensates the average deficient energy supply (200 W) experienced between the load and the generation and reaches a steady state current of 8.34 A at $t = 1.2$ sec with an initial overshoot as shown in Figure 3.13 (a). Comparatively, the BESS instantly reaches a steady state current at 10 A $t = 1$ sec with negligible duration of the current overshoot, as shown in Figure 3.13 (b). Similarly, the SCSS current that provides short-term transient power compensation and operates until the BESS reaches its steady state condition.

The efficacy based comparison between these two methods is firstly done on the basis of voltage magnitude and its degree of deviation at the DC bus (V_{dc}). As observed in Figure 3.13 (a)-(b), the LPF strategy is unable to optimally regulate V_{dc} during transient conditions and a transient voltage drop of 46 V is experienced, whereas in the proposed method it is 47.5 V. This is mainly due to the slow dynamics of BESS, that inherently curtails the required response resulting in uncompensated current that contributes to the voltage deviation and negatively impacts the BESS life cycle. Secondly, the impact on the BESS % SoC decrease

in the proposed method is less as compared to the LPF method at the end of the operational analysis.

CHAPTER 4

VOLTAGE REGULATION BY ACTIVE - REACTIVE POWER MANAGEMENT OF PV THROUGH INVERTERS

Overview: The power flow variations due RES causes voltage issues. Local voltage violations are worse in case of low and medium voltage distribution networks, especially at high levels of RES. Firstly, this chapter outlines the network dynamics associated with the integration of RES-DG and the line characteristics of the network that contributes towards the voltage violations. Further, a volt/var based active-reactive power management strategy is proposed and tested on various R/X ratios. Further, suitable incorporation of BESS is also proposed, when the volt/var compensation reduces the power quality of the system.

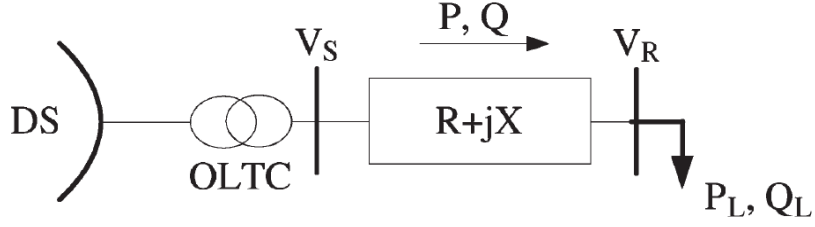


Figure 4.1: Typical two bus distribution network.

4.1 Voltage Dynamics with High DG Penetration

The high resistance to reactance (R/X) characteristics in distributed networks results in a higher percentage voltage drops as compared to the transmission networks. Considering a simple two bus system connected to the distribution substation (DS) through an OLTC (Figure 4.1); here, $\hat{V}_S$ and $\hat{V}_R$ are the sending end voltage and receiving end voltage respectively; P and Q are the active and reactive power flow through the line respectively; and the real and reactive power of the load are P_L and Q_L respectively. So, $\hat{V}_S$ can be written as

$$\hat{V}_S = \hat{V}_R + \frac{RP + XQ}{\hat{V}_S^*} + j \frac{XP - RQ}{\hat{V}_S^*} \quad (4.1)$$

Therefore the voltage drop is expressed as

$$\Delta \hat{V} = \hat{V}_S - \hat{V}_R = \frac{RP + XQ}{\hat{V}_S^*} + j \frac{XP - RQ}{\hat{V}_S^*} \quad (4.2)$$

The voltage drop can be considered equal to the real part of the voltage drop

given in (4.2) as the phase difference between $\widehat{V}_S$ and $\widehat{V}_R$ is negligible [190]. Also, considering the sending end bus as the reference bus, the voltage angle is zero ($\widehat{V}_S^* = |V_S| = V_S$). Therefore (4.2) is equated as

$$\Delta V \approx \frac{RP + XQ}{V_S} \quad (4.3)$$

Further, sending-end voltage when considered as the base voltage, then (4.3) is represented as (4.4), hence representing the dependency of voltage drop (ΔV) on R and X .

$$\Delta V \approx RP + XQ \quad (4.4)$$

Accordingly, with the formulation of voltage variation in large distribution networks; considering ΔV_{ij} , R_{ij} and X_{ij} are the voltage drop, resistance and reactance from i th to j th buses; P_{ij} and Q_{ij} are the active and reactive power flow through i th and j th bus; and V_i is the voltage at the i th bus .

$$\Delta V_{ij} \approx \frac{R_{ij}P_{ij} + X_{ij}Q_{ij}}{V_i} \quad (4.5)$$

Firstly, the process of power transfer from the DG (at the receiving-end) is most likely to increase the respective node voltage in comparison to other buses. Therefore V_R will be

$$V_R \approx V_S + RP + XQ \quad (4.6)$$

Observing a change in the direction of the power flow, the node voltage at

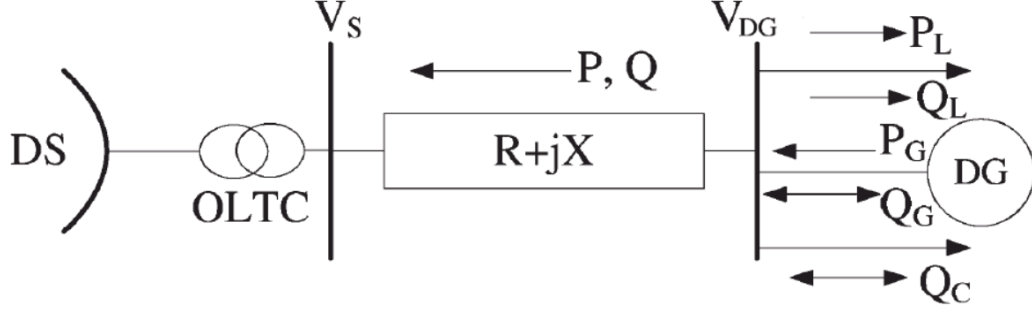


Figure 4.2: DG-integrated two-bus distribution network.

the terminal of DG will be higher than the sending-end voltage; here, taking the voltage at DG terminal, generated active and reactive power, and the reactive power of shunt compensators as V_{DG} , P_G , Q_G and Q_C , respectively (Figure 4.2). The voltage drop is formulated as

$$\Delta V = V_{DG} - V_S \approx \frac{RP + XQ}{V_{DG}} \quad (4.7)$$

where, $P = (P_G - P_L)$, and $Q = (\pm Q_C - Q_L \pm Q_G)$. Now, considering in terms of per unit and taking V_{DG} as the base voltage; (4.7) can be written as

$$\Delta V = V_{DG} - V_S \approx R(P_G - P_L) + X(\pm Q_C - Q_L \pm Q_G) \quad (4.8)$$

In terms of power flow, the DGs always export active power and might export/import reactive power. The load always consumes the active and reactive power while, the shunt compensators import or export reactive power. Therefore the reactive power capability of DGs depends on the type of energy resources. For

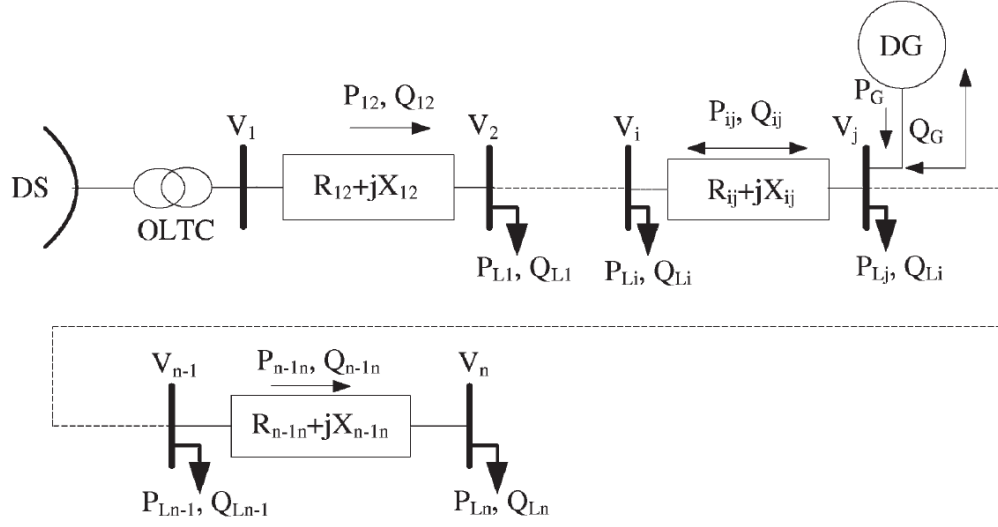


Figure 4.3: DG-integrated n-bus distribution network.

instance, considering the case of CHP, the excitation control possess the capability to export reactive power as per the system requirement. However, considering the case of DG as wind turbine. The induction generator operation requires a reactive power source to maintain the voltage stability. Finally, PV operating at unity power factor does not export/import or require reactive power.

In large networks with high level of DG penetration (Figure 4.3). The voltage variation can be obtained in the similar way as discussed in (4.5); here taking, P_{Gj} and Q_{Gj} as the generated active and reactive power by the DG respectively; P_{Lj} , Q_{Lj} as the active and reactive load at bus j ; and Q_{Cj} as the shunt at the j th bus of the radial distribution network. The voltage variation can be written as

$$\Delta V_{ji} \approx \frac{R_{ij}(P_{Gj} - P_{Lj}) + X_{ij}(\pm Q_{Gj} \pm Q_{Cj} - Q_{Lj})}{V_j} \quad (4.9)$$

The per unit expression of (4.9) can be equated as

$$\Delta V_{ji} \approx R_{ij}(P_{Gj} - P_{Lj}) + X_{ij}(\pm Q_{Gj} \pm Q_{Cj} - Q_{Lj}) \quad (4.10)$$

The formulated equation can be used to study the effects of integrating DGs in a distribution network and hence mitigate its effect.

4.2 Reactive Power Support Through PV Inverter and the Proposed Strategy

Usually in accordance to past supervision prescribed by IEEE 1547 standard towards restriction of voltage regulation by DGs, most of the inverters were allowed to operate at a fixed unity power factor (φ_i); with negligible reactive power injection/absorption, in both small and large renewable DG interconnections [191]. However, due to renewable intermittency, such active power injection instigates a trend of undesirable steady-state voltage variations during ramped DG output or light loading periods. Hence the recent IEEE 1547 standard amendment allows voltage regulation through controlled var injection [192, 193].

The inverter reactive power capability at the j th bus is limited by (4.11), where S_{Gj} is the fixed apparent power and P_{Gj} is the variable active power generation through the PV. Therefore at an interval, the PV inverter is capable of injecting/absorbing a specified amount of reactive power (Q_{in}):

$$Q_{in} \leq \sqrt{S_{G_j}^2 - P_{G_j}^2} \quad (4.11)$$

This operation of inverters is categorized under voltage support, ancillary services provided by renewable installations. Most of the ancillary services that facilitate active power balance and frequency support such as system scheduling, dispatch, energy imbalance services, voltage support, etc. are dynamically competitive in the energy market. However, ancillary services such as black start and reactive power supply are classified as cost-based services, that is, remuneration for additional services [194].

In most European countries the deregulation and liberalisation of the electricity markets brought about numerous opportunities for small as well as large scale integration and selling of electricity with renewable installations. Apart from a fixed tariff payment, other forms of premium tariffs has been introduced that were technology-specific for system stability [195]. In addition, countries such as Germany and Spain have introduced time - differential or demand - oriented tariff payment for services that improve system stability, these incentives also include the provision of reactive power by the owners [196].

Furthermore, with the mandates of IEEE 1547 standards, PV inverters ratings are oversized to about 11 % to the PV ratings, for operational stability [191,197]. Though some studies present the advantages of PV inverters and its competence, both technologically and economically, in comparison to conventional [198] utility based tariff to customers are distinctive based on regional and provincial rules and

regulations. Based on rules implemented in different countries a structured framework and legal proceedings exists for the procurement of reactive power only for high voltage transmission lines, through the utility or contractors. Nevertheless, residential based reactive power procurement are implicit in the tariff payments of the customers [199].

Some utilities achieved voltage regulation by specifying a fixed predetermined reactive power compensation capability of the inverters. This is achieved either through “fixed Q” and or “fixed $\cos\varphi$ ” methods [200]. While these methodologies do not actively mitigate the voltage variations, with intensive study before interconnection, they can however establish reactive power flow between the interconnection of the grid and DGs and hence mitigate the voltage fluctuations due to intermittent DG active power output. Accordingly, more inclusive form of active voltage regulation can be established with the modification of the above methodologies as a function of local variables. Based on numerous control theories, a relation between system variables and parameters can be established. For instance, $\cos\varphi(P_G)$ method, wherein the power factor is actively adjusted as a function of the locally measured active power injected into the grid by the DGs; thereby limiting the impact of active power variation and simultaneous mitigation of the voltage variation through reactive power compensation.

In similar terms, the variation of the inverter’s power factor, $\cos\varphi$ can also be established as a function of combined local active power level (P_G) and the X/R ratio of the distribution network $\cos\varphi(P_G, R/X)$ [25]. Though the control setting

is dependent on the performance evaluation study, each PV inverter has a unique control setting exclusive to their respective feeders impedance at the point of DG interconnection.

Since the aim here is to effectively and flexibly regulate the voltage, “volt/var” or $Q(V)$ method is instigated in this research. In this method, a respective PV inverter injects/absorbs the reactive power with respect to the voltage measurement the point of interconnection; hence, providing a customized local var response. Further, reactive power capability can be utilized at its full rating at night, in this case at 6-kVAR, when PV is not generating any power. However, during PV production the voltage should be regulated with minimal active power curtailment to facilitate high economic gains.

The objective of the reactive power support (RPS) from the PV inverter is to regulate the critical bus voltage. Usually in a radial distribution network, as shown in Figure 2.1 the bus located at the end of the RDN are susceptible to experience the worst degree of voltage violation, that is, the n^{th} bus. Therefore, the inverters located at the farthest end have the maximum impact, that is, the inverters at n^{th} and $(n - 1)^{th}$ bus have more impact mitigation of the voltage rise as compared to the inverters at the first or the second bus. In addition, there are power factor constraints for grid-tied inverters pertaining to the utility grid-code as well as the feasibility towards the active power curtailment required for providing the RPS. Consequently, placement and activation of RPS on each bus of the RDN or at the location of RES, is more favourable for maintaining the power

factors of the PV inverters within an acceptable limit. Therefore, we propose a local voltage control technique for active - reactive power management of the PV inverters based on volt-var principle as, where α_L is the active loading constant derived from Figure 4.6 and varies in the range of (1 - 10), according to the active power curtailment required from the PV inverters for voltage regulation; V_j is the corresponding bus voltage.

$$Q_{in} = \begin{cases} \alpha_L S (1 - e^{(1 - V_j)}), & 1.05p.u. < V_j < 0.95p.u. \\ 0 & \text{otherwise} \end{cases} \quad (4.12)$$

$$P_{Gj} = \begin{cases} \sqrt{S^2 - |Q_{in}|^2}, & 1.05p.u. < V_j < 0.95p.u. \\ P_{Gjmax}, & \text{otherwise} \end{cases} \quad (4.13)$$

Therefore, the designed controller maintains a minimum curtailment of PV active power. The controller is designed for PV inverters to inject reactive/absorb power when voltage violations occur with minimum active power loss. During the intervals in which the voltage is under the permissible voltage limit, the operation of the controller is kept at a minimum and close to unity. In case of voltage violation, an exponential formulation that is a function of system instantaneous voltage (V_j) variation, this is applied locally at the respective solar PV inverters. This function is to comprehend sinusoidal curve of the PV generation curve that effects the grid voltage.

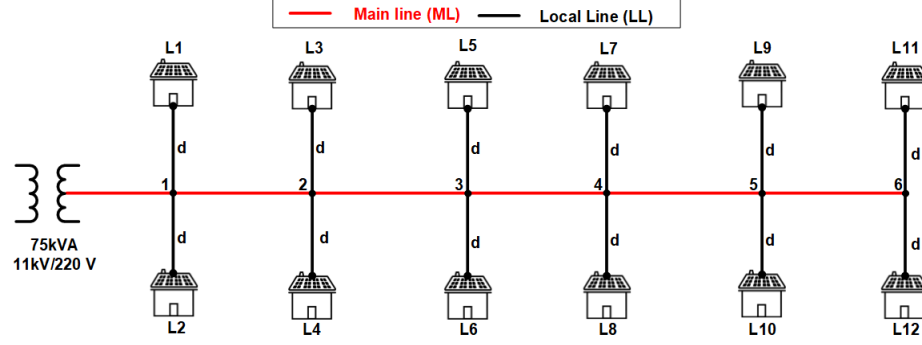


Figure 4.4: Radial distribution network with 6 bus.

4.3 Modelling of the Test System

Based on Figure 2.1, a radial distribution network with 6 buses is developed to demonstrate the effectiveness of the proposed control strategy. As shown in Figure 4.4, the power is supplied through a to RDN is supplied through a 75-kVA 11kV/220V transformer. Two house loads (L) are connected at each bus with a maximum load demand of 3 kW. The load profile for each house is different and modelled in accordance to a typical house profile, with [201]. Further, each of the 12 houses (L1-L12) are equipped with 6 kVA rooftop PV system, to emulate a severe over-voltage condition. The analysis is performed on an hourly data profile of solar and load as shown in Figure 4.5 and the permissible voltage range is 0.95 and 1.05 p.u. ($\pm 5\%$ of the base voltage).

In this study, two scenarios are considered, based on the variation of R/X ratios and the distance. The first scenario (urban), considers R/X close to unity ratio and the distance (d) between the main line (ML) and each house is 20 m. Accordingly, in the second scenario (rural), d is 100 m and the R/X ratio of the line is 5, as depicted in Figure 4.4.

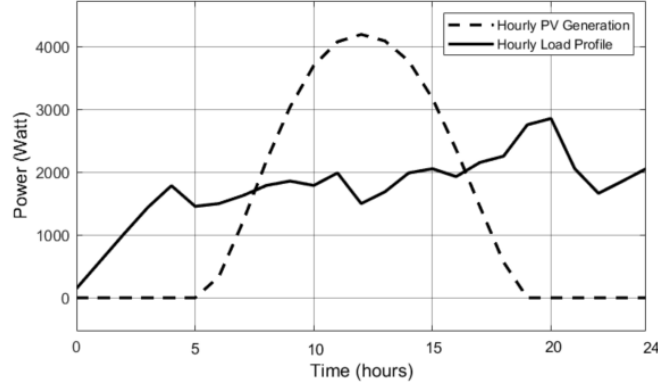


Figure 4.5: Hourly Load and PV Generation.

4.3.1 Impact of the Line Characteristics on the Effectiveness of Inverter Reactive Power Capability

The basis of control theory design to understand and mitigate the effects of voltage variations due to high DG integration is formulated on 4.1. Further, from equation (4.8) representation as (4.14) it can also be inferred that the level of DG or RES integration is dependant on the sending-end voltage (V_{DS}), voltage at the receiving-end, transmission line conductor size and its length.

$$P_G \approx \frac{V_{DG} - V_S + RP_L - X(\pm Q_C - Q_L \pm Q_G)}{R} \quad (4.14)$$

To quantify the limitation that the line characteristics have on the capability of the reactive power compensation of the inverters simulations have been performed on the test RDN network (Figure 4.4) to find a critical R/X ratio. Firstly, the percentage increase in line losses are calculated for various R/X values. Then, unless the voltage violation is eliminated, reactive power is injected that is gradually

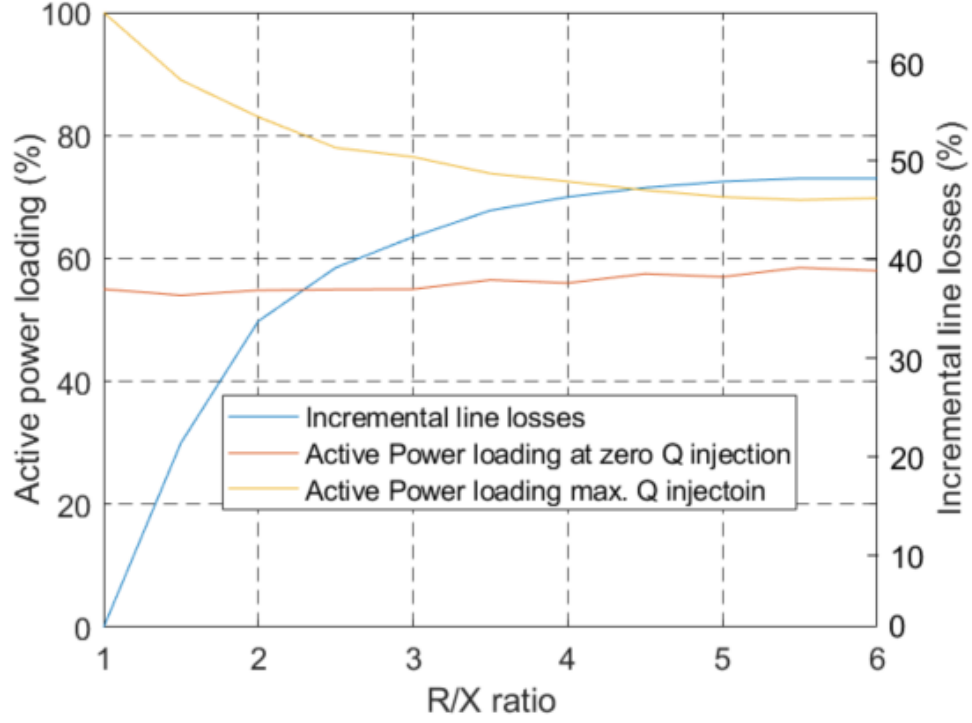


Figure 4.6: Variation of losses and active power loading with the R/X ratio.

varied from 0 to 0.8 power factor (that is 3.6 kVAR). Finally, in case the voltage violation is still present, then the active power loading is decreased. Therefore, from Figure 4.6, it is primarily observed that the with the increase in R/X ratio, the active power loading has to be decreased. Further, at higher R/X ratios (above 4.5), the peak value of the active power should be curtailed by around 70%. Similarly, line losses increase with the increment in the resistance of the line. In addition, it can also be observed that after a certain R/X value the incremental line losses increase even with a constant reactive power injection.

Table 4.1: Voltage Profile of Rural Scenario with Proposed Controller

	Bus voltage (p.u.)					
Hrs	1	2	3	4	5	6
1	0.98	0.98	0.97	0.97	0.97	0.97
2	0.98	0.98	0.97	0.97	0.97	0.97
3	0.98	0.98	0.97	0.97	0.97	0.96
4	0.98	0.98	0.97	0.97	0.96	0.96
5	0.98	0.98	0.97	0.98	0.96	0.96
6	0.98	0.98	0.97	0.98	0.96	0.97
7	1.00	0.99	0.99	0.99	0.99	0.99
8	0.98	1.00	1.00	1.01	1.01	1.01
9	1.00	1.00	1.01	1.02	1.02	1.02
10	0.99	1.00	1.02	1.02	1.03	1.03
11	0.99	1.00	1.02	1.03	1.03	1.04
12	0.99	1.00	1.02	1.03	1.04	1.04
13	0.99	1.00	1.02	1.03	1.04	1.04
14	0.99	1.00	1.02	1.03	1.03	1.04
15	0.99	1.00	1.01	1.02	1.03	1.03
16	0.99	1.00	1.01	1.01	1.02	1.02
17	0.99	0.99	0.99	1.00	1.00	1.00
18	1.00	0.99	0.98	0.98	0.98	0.98
19	1.00	0.99	0.98	0.98	0.97	0.96
20	1.00	0.98	0.98	0.97	0.97	0.96
21	1.00	0.99	0.98	0.97	0.96	0.96
22	1.00	0.99	0.98	0.97	0.96	0.96
23	1.00	0.99	0.98	0.97	0.97	0.97
24	1.01	0.99	0.98	0.98	0.97	0.97
Min. P.F of Inverter	0.97	0.97	0.97	0.95	0.95	0.94

4.4 Simulation and Discussion

4.4.1 Voltage Profile with High PV penetration

The simulation has been carried out for both the scenarios. The resultant voltage profile with high PV penetration are shown in Figure 4.7. Moreover, since the worst voltage profile is at the end of the distribution feeder, for simplicity, only the voltage profile of the houses located at bus 6 are shown in Figure 4.8. When

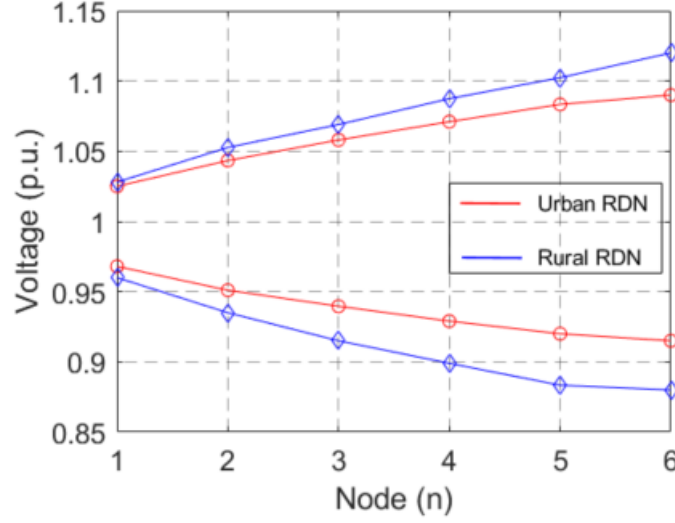


Figure 4.7: Voltage profile across the RDN during peak PV generation and peak loading conditions.

the inverter operates at unity power factor, it can be observed that the voltage exceeds the permissible limit of 1.05 p.u. during peak PV generation at 12th hour (noon). The load at this interval is 1.85 kW as compared to 6 kW of the power generated by the PV.

Similarly, at night when PV does not generate power, during the peak loading interval observed at 20th hour (i.e at 8 P.M) the voltage acutely drops below the lower permissible limit of 0.95 p.u. and the load demand observed is 2.8 kW. The voltage violation at both instant is much more worse in case of rural RDN, hence quantifying the relation and the impact of line characteristics on the voltage profile of a distribution network.

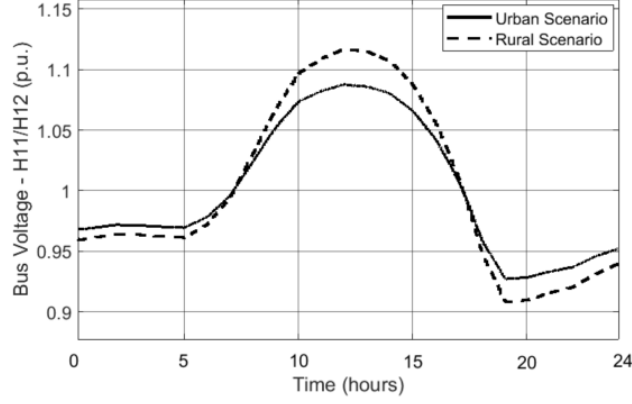


Figure 4.8: Hourly voltage profile for bus 6.

4.4.2 Hosting Capacity

Utility networks are contrived based on a centralized power generation with unidirectional optimization of power flow. The integration of renewable based distributed generation will presumably disrupt the normal operation of the utility network [202]. Correspondingly, high level of PV integration will possibly lead to voltage issues, likely increasing system harmonics and thermal stress [203]. Furthermore, transient PV power generation causes wearing of the equipments with incremental system losses due to additional switching of capacitors and tap changes [204].

For an economical integration of PVs numerous distributed generation technologies present distinctive active-reactive management capabilities to facilitate increased PV penetration. In any case, the system performance may improve or deteriorate either with respect to different technical aspect. Nonetheless, as long as the power quality of the system is within acceptable limits the deterioration is not a direct concern. In this respect, analysis of hosting capacity provides a

quantified feasibility of a respective distributed generation technology [205].

The general approach for determining the hosting capacity starts with the selection of performance index or indices. This index can be based on international or national standards (IEEE 1366, IEEE 1547, EN50160, IEC 61000-3-11, etc), but can also be selected internally based on the interests of the utilities owners/operators [206]. Different methodologies are implemented to study the impact of PVs on the grid performance (such as, time series, deterministic or stochastic) [207, 208]. In the literature, the index usually considered ranges from over-voltage, dynamic voltage, undervoltage, current or voltage harmonics, supraharmonics thermal overloads, system protection framework and system losses [209]. The steps involved to cumulate the hosting capacity can be broadly summarized as:

- Selection of singular or multiple performance indices.
- Determine the set of boundary values, i.e. acceptable limits.
- Analysis of the system using power flow with variable amount of PV integration.
- Identification and formulation of the amount of PV penetration at which the system violates the acceptable limits.
- Obtain the hosting capacity.

This section presents the hosting capacity considering under voltage and over voltage criterion for the RDN under consideration. Firstly, considering that each

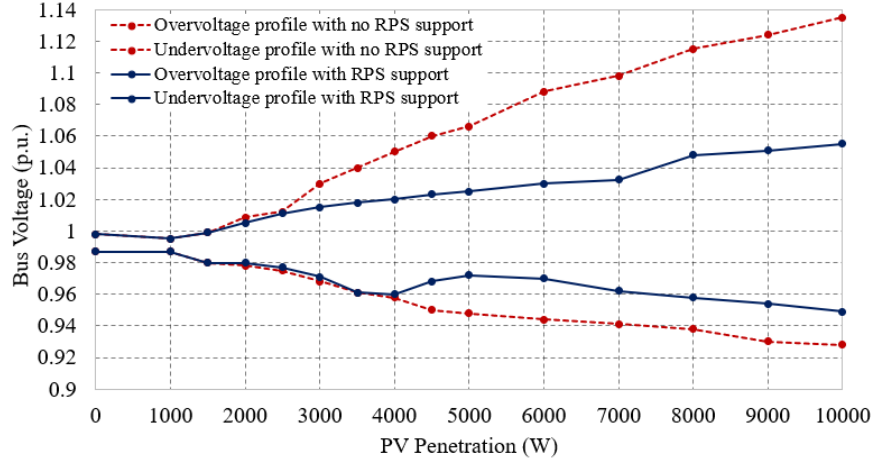


Figure 4.9: Hosting capacity based on overvoltage and undervoltage criterion.

residential bus installs a localized PV, the analysis is performed with step increment to size of the PVs. Based on the results obtained, as depicted in Figure 4.9, the maximum hosting capacity of that the system can hold is at 116.67 % at 3.5 kW. The system observes overvoltage at higher rating, that is, overvoltage occurs at the feeder end at 4 kW and undervoltage issues are introduced with PV ratings 4.5 kW and above. Accordingly, with further increment in the PV rating more buses are effected and violate the voltage criterion as shown in Figure 4.10.

The implementation of proposed active - reactive power management the hosting capacity increases to 266.67 % observed at 8 kW PV rating. The voltage profile under these PV ratings comply to the over voltage and under voltage criterion of the hosting capacity, as shown in Figure 4.9. Nevertheless, above this prescribed PV rating an overvoltage violation occurs on the bus at the feeder end (at 9 kW PV rating), with overvoltage proliferation at the penultimate bus with additional undervoltage violation (at 10 kW PV rating).

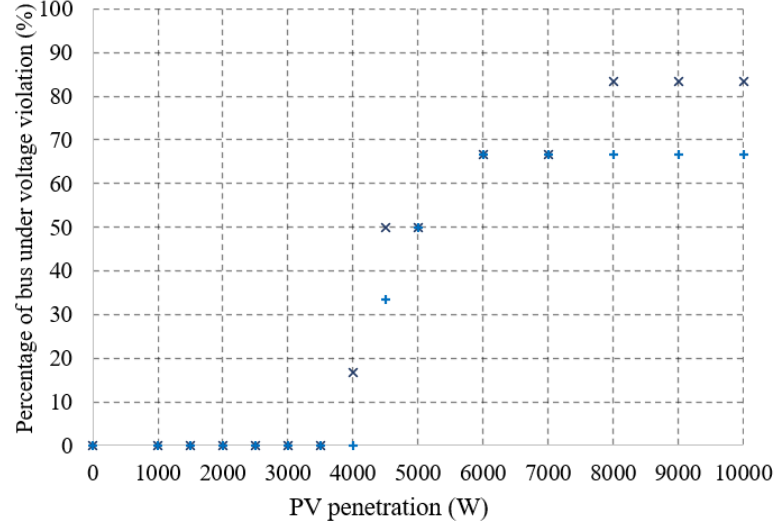


Figure 4.10: Percentage of buses effected by voltage violation.

Similarly, an analysis is performed to highlight the hosting capacity of each individual bus. The PV is placed individually at each bus and the hosting capacity is calculated with step increment in the PV ratings.

4.4.3 Voltage Regulation in Urban Scenario based on Active - Reactive power Management by the PV Inverters

The effectiveness of the controller has been performed for the urban scenario. The proposed controller is installed at all of the 12 houses in the test RDN for coordinated control of the active and reactive power of the PV inverters. In this case, the voltage violation is experienced from bus 3 to 6, ranging from 0.91 p.u. and 1.09 p.u. lower and upper voltage values (Figure 4.7). As shown in Table 4.1, based on the proposed strategy, the locally controlled inverters adjust the

reactive power injection/absorption according to the requirement of the system in real time. Hence the voltage violation between the 12th and 13th hour of the day is substantially regulated from 1.06 p.u. to 1.02 p.u., in accordance the lower limit violation is regulated from 0.96 p.u. to 1.04 p.u. that is well within the permissible limit. Further, the active power curtailed is not substantial as observed from the power factor (P.F) obtained for each inverter placements.

4.4.4 Co-ordination of Active - Reactive Power between PV - Inverters and Batteries for Voltage Regulation in Rural Scenario

In this section, voltage regulation of rural RDN is presented considering PV-inverter and BESS. Henceforth, all the houses connected to the feeder are additionally installed with BESS for a systematic support to improve the voltage profile as the RPS is not sufficient with increased R/X ratios and load distances.

The operation of the BESS is such that, it charges and stores the surplus power during the day time to obviate over-voltage condition, above 1.05 p.u. Accordingly, the BESS supports the under-voltage conditions that usually occurs at 15th or 16th hour of the day as the PV production gradually decreases and the voltage falls below 0.95 p.u. Therefore, the operation involves voltage regulation primarily through the PV inverters and BESS operates as a secondary means of support.

Since, the houses connected at the same bus project a similar characteristics,

for graphical simplicity, the results obtained consisting of voltage profiles, reactive power support and the charge and discharge of battery, of only six houses are shown from Figures 4.11 to 4.34. The proposed controller has been simulated and observed for the rural scenario.

Firstly, the voltage violation in this scenario is substantially high that occurs from bus 2-6 (Figure 4.7), ranging from 0.88 - 1.2 p.u. This over-voltage and under-voltage condition is effectively maintained and regulated within 0.98 - 1.03 p.u. range that is well within the acceptable upper and lower permissible voltage limit.

Furthermore, it can be observed that the increased line distance and R/X ratios has broadly more effect and contribution towards the voltage deviation in comparison to loading profile. Consequently, the reactive power contribution and the subsequent BESS storage requirement increases along the nodes of the RDN. The BESS facilitates a smooth transition during the peak PV generation and peak loading time.

Considering, the demand - generation profile the BESS operation is minimal, mainly due to low solar irradiance and with gradual increase mainly at the 10th hour of the day a progressive charging of BESS occurs. Mostly, during these peak PV production intervals majority of the surplus power is curtailed from the grid to regulate the voltage deviation and directed towards BESS charging.

This exclusively reduces PV's active power contribution towards voltage deviation during these intervals. Similarly, in combination of reactive power support

the BESS ensures a smooth transition spanning the gradual decline of the PV generation. In this analysis, a total requirement of 42.51 kWh of battery has been calculated, with the highest BESS size of 5.33 kWh required at the end of the RDN, at bus 6.

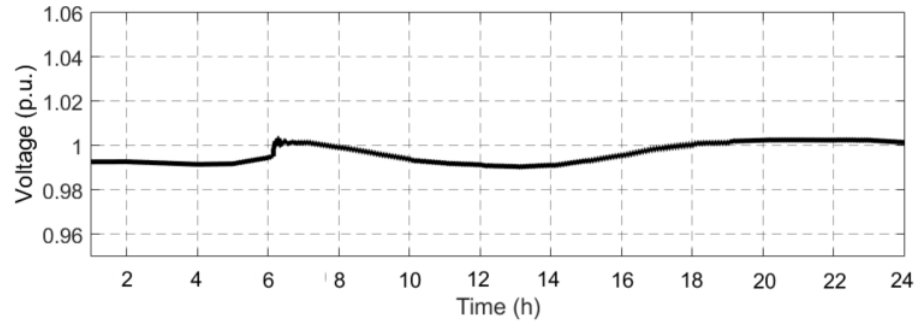


Figure 4.11: Voltage profile at bus 1 with the proposed PV inverter - BESS power coordination and control.

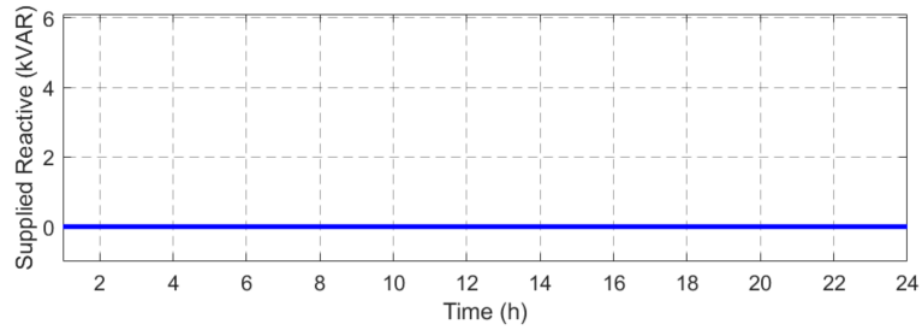


Figure 4.12: Reactive power support provided by the PV inverter at bus 1.

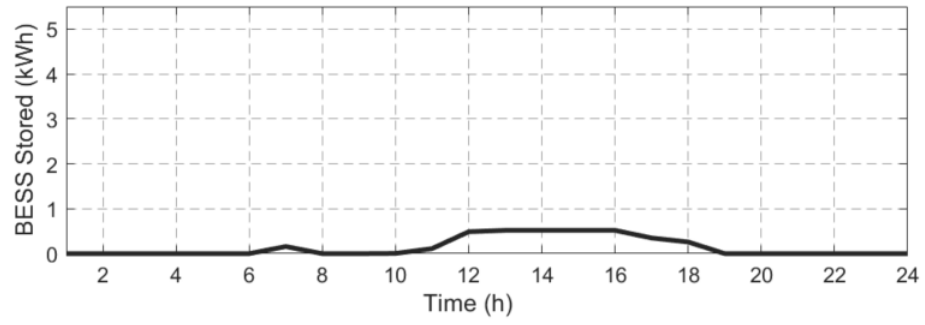


Figure 4.13: BESS stored energy with coordination to the PV inverters at bus 1.

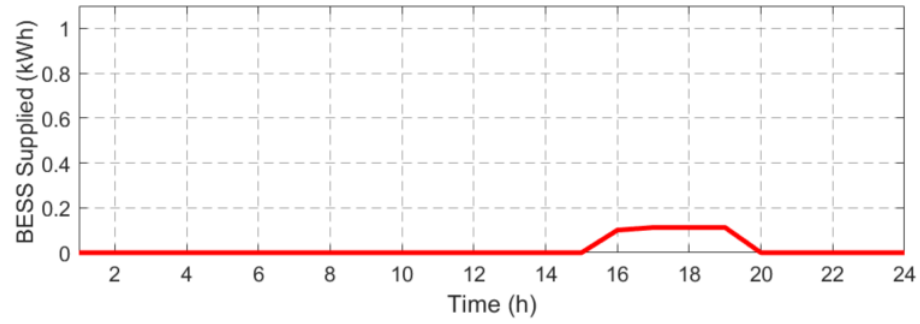


Figure 4.14: Energy Supplied by the BESS coordinated with the PV inverter at bus 1.

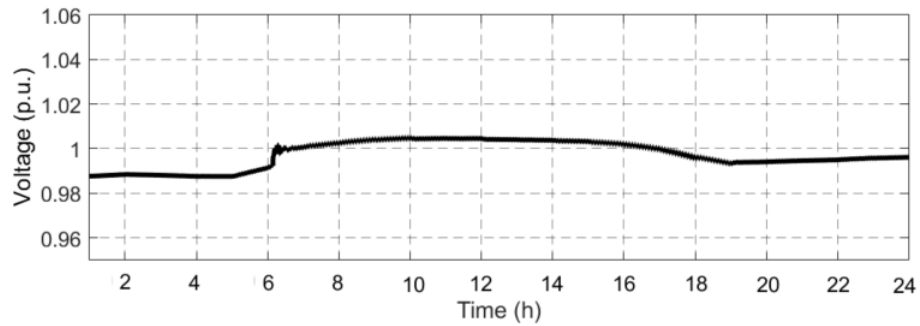


Figure 4.15: Voltage profile at bus 2 with the proposed PV inverter - BESS power coordination and control.

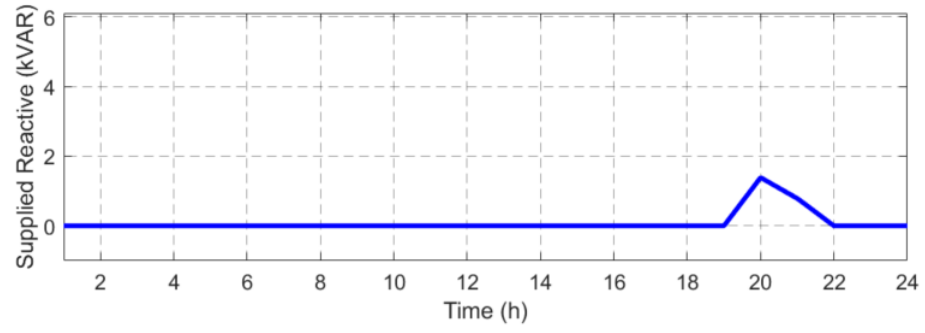


Figure 4.16: Reactive power support provided by the PV inverter at bus 2.

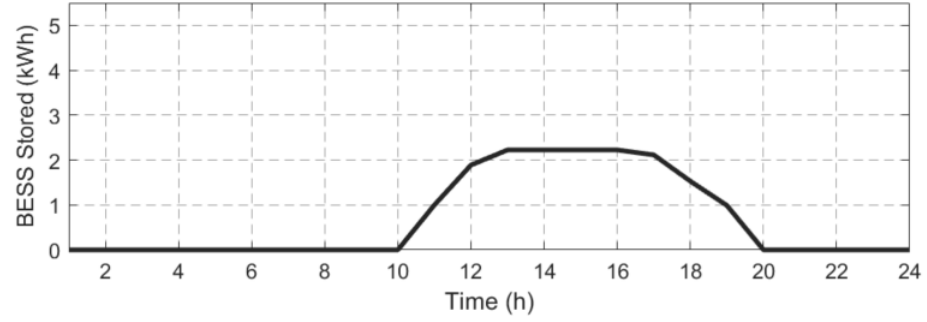


Figure 4.17: BESS stored energy with coordination to the PV inverters at bus 2.

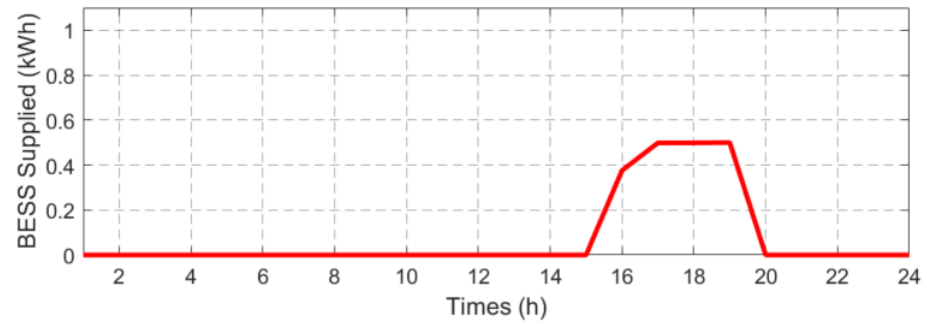


Figure 4.18: Energy Supplied by the BESS coordinated with the PV inverter at bus 2.

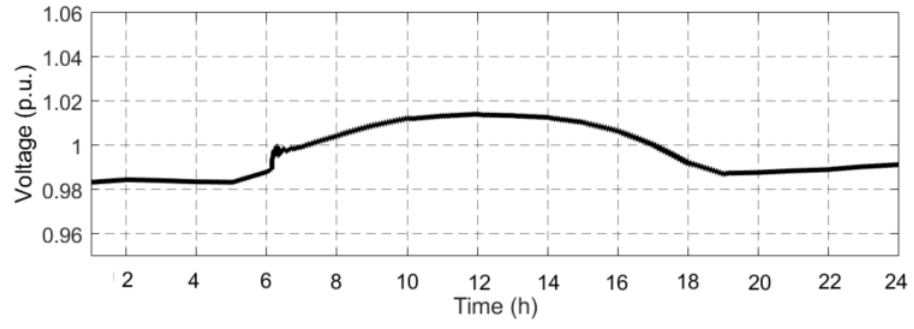


Figure 4.19: Voltage profile at bus 3 with the proposed PV inverter - BESS power coordination and control.

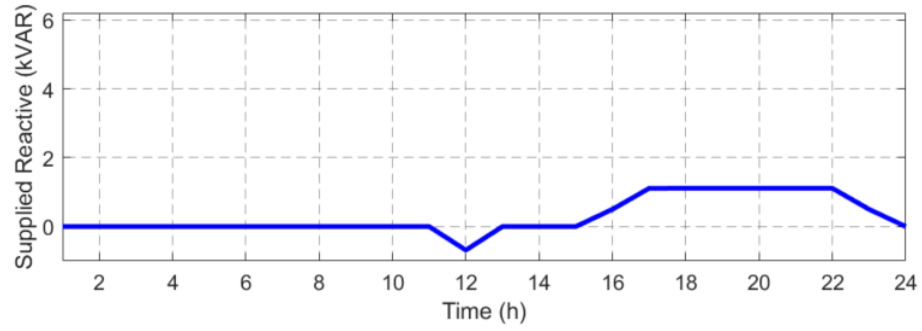


Figure 4.20: Reactive power support provided by the PV inverter at bus 3.

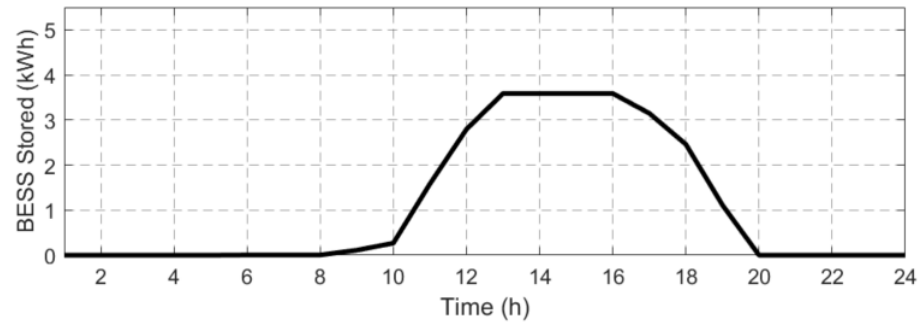


Figure 4.21: BESS stored energy with coordination to the PV inverters at bus 3.

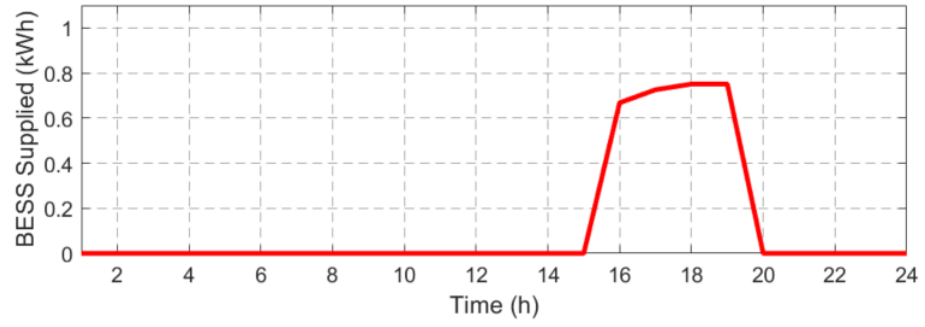


Figure 4.22: Energy Supplied by the BESS coordinated with the PV inverter at bus 3.

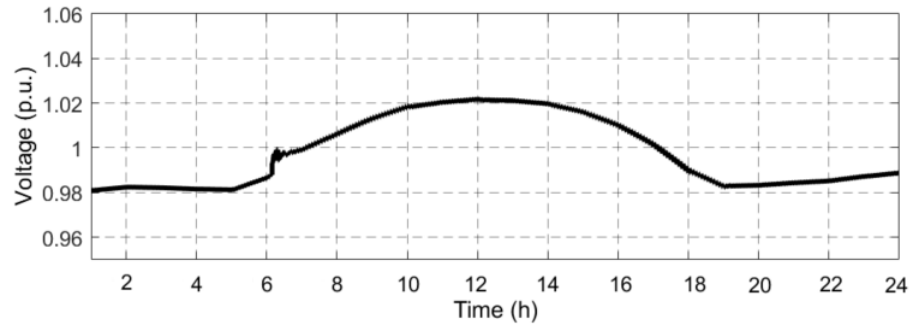


Figure 4.23: Voltage profile at bus 4 with the proposed PV inverter - BESS power coordination and control.

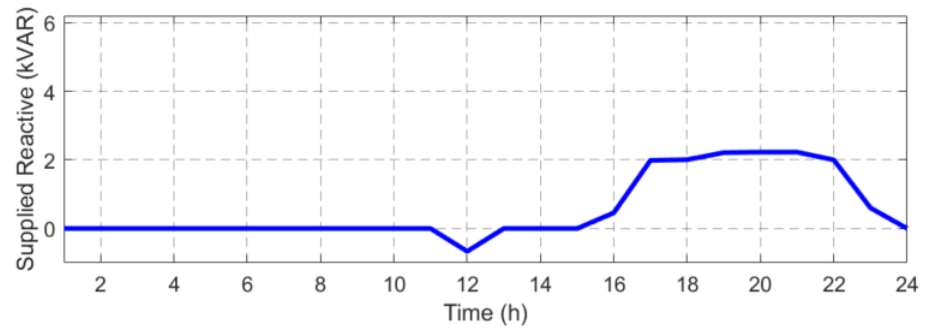


Figure 4.24: Reactive power support provided by the PV inverter at bus 4.

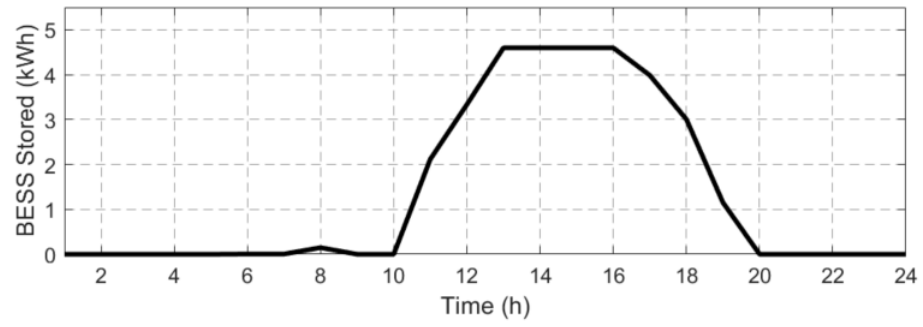


Figure 4.25: BESS stored energy with coordination to the PV inverters at bus 4.

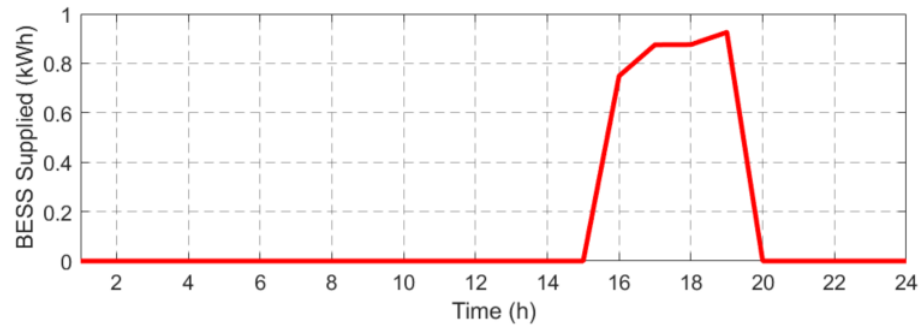


Figure 4.26: Energy Supplied by the BESS coordinated with the PV inverter at bus 4.

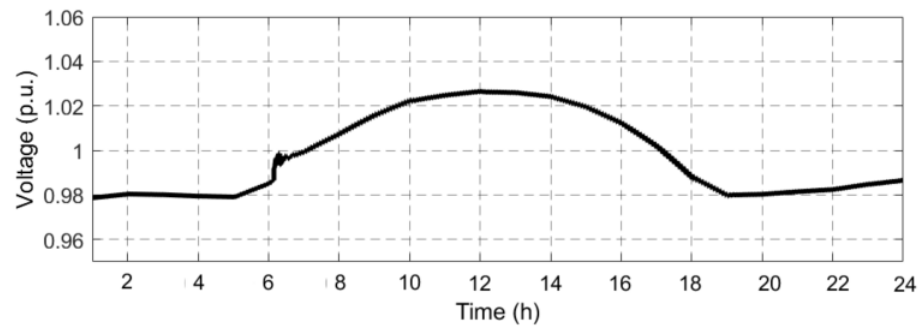


Figure 4.27: Voltage profile at bus 5 with the proposed PV inverter - BESS power coordination and control.

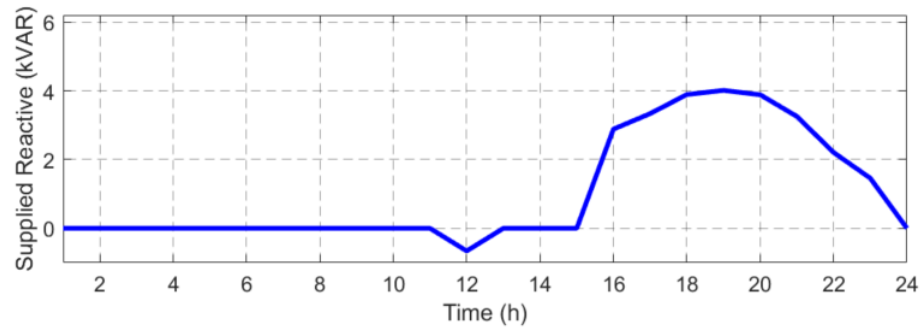


Figure 4.28: Reactive power support provided by the PV inverter at bus 5.

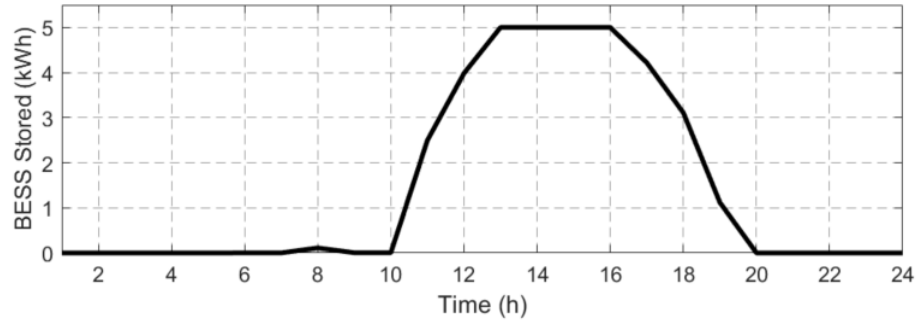


Figure 4.29: BESS stored energy with coordination to the PV inverters at bus 5.

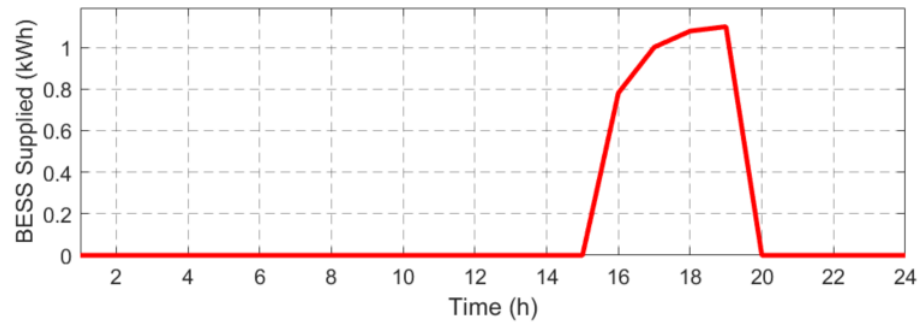


Figure 4.30: Energy Supplied by the BESS coordinated with the PV inverter at bus 5.

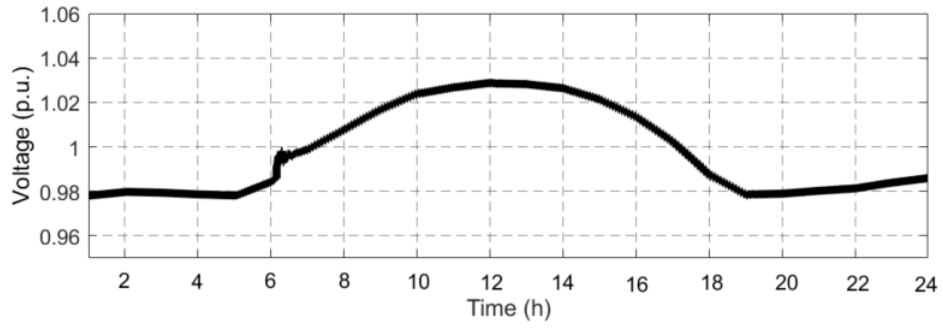


Figure 4.31: Voltage profile at bus 6 with the proposed PV inverter - BESS power coordination and control.

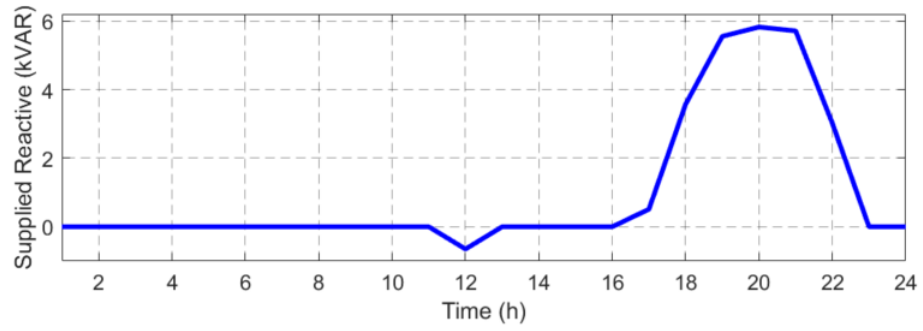


Figure 4.32: Reactive power support provided by the PV inverter at bus 6.

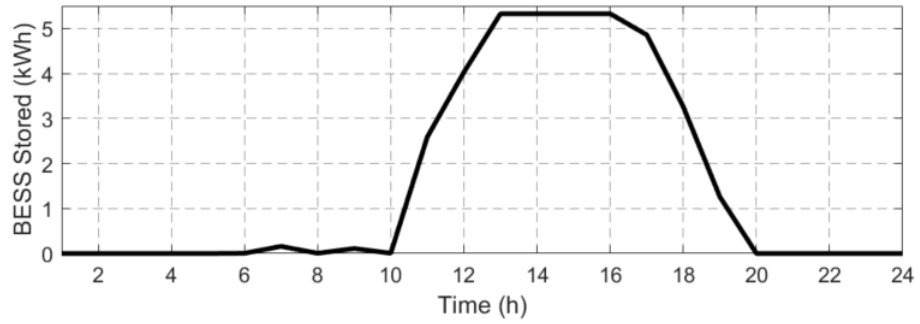


Figure 4.33: BESS stored energy with coordination to the PV inverters at bus 6.

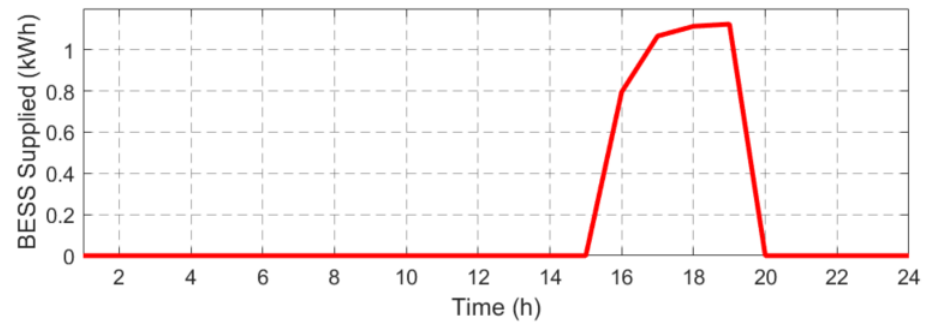


Figure 4.34: Energy Supplied by the BESS coordinated with the PV inverter at bus 6.

CHAPTER 5

CONCLUSION

In this thesis research work, we firstly presented an instructive review to outline and recommend suitable energy storage systems based on their technical characteristics considering the high ambient temperatures of the Kingdom. Numerous types of battery technologies have been presented based on which vanadium redox flow batteries is recommended as the most promising in case of utility grade large-scale renewable energy source (RES) integration into the system, closely followed by sodium-sulphur battery technologies.

The complementary characteristics of battery energy storage system (BESS) and supercapacitor energy storage system (SCSS) has been discussed with a comprehensive review comprehensive review, outlining the superior storage capabilities that can be achieved with the hybridization of these two technologies. It can postulated that

- The resultant hybrid energy storage system (HESS) has the applicative potential in various domains of RESs, electric vehicles and wireless power tech-

nologies.

- Addition of BESS-SCSS-HESS serves as an effective energy buffer that meticulously helps in output power smoothing of solar and wind energy resources. This not only improves the power quality of the grid but also significantly reduces the dependency on forecast values, increasing the reliability to establish a large-scale renewable power grid in terms of economical dispatchability.
- The improved response of the hybrid energy storage serves as pertinent support to the grid-tied inverters and serves as extremely reliable backups in terms of short-term faults in the power system.
- In case of electric vehicles (EV), where autonomy is the key commercialization factor, SCSS acts as an energy buffer during abrupt acceleration and hill climbing operations, with significant reduction of EV weight.
- The characteristics of SCSS can be more effectively used to store energy produced during regenerative braking, increasing the mileage of EVs.

The research work proposed a control technique for DC bus voltage regulation renewable based microgrid by using hybrid BESS-SCSS. The technique conferred the development of hybrid battery-supercapacitor (BESS-SCSS), as an energy buffer to maintain the demand-generation mismatch, further outlining a decoupled based power allocation strategy to enhance and harness their selective dominant characteristic. The proposed controllers are based primarily on Type

II k-Type compensators and non-linear PI controller for optimal power allocation between BESS and SCSS respectively. The effectiveness and robustness of proposed control strategy has been analysed and validated to regulate the DC bus voltage under different scenarios of loading conditions. Moreover, the results have been additionally compared with existing LPF based control technique.

- The proposed controller enhanced the voltage regulation in various case studies of abrupt/transient demand-generation variation. This also enables extended operational period.
- In comparison, to the benchmark low pass filter (LPF) strategy experienced a significantly reduced voltage magnitude and degree of voltage deviation is achieved.
- The BESS current stress is observably lower, obviating the sudden partial charge/discharge due to current overshoots; hence reducing its temperature variations, the associated losses and degradation.
- Although the proposed methodology is applied for solar, it is quite general and can be implemented for mitigating the transient effects of other renewable based power fluctuations and hence maintain the power quality supplied to the load.

Finally, an active-reactive power management strategy is presented for local voltage regulation in radial distribution network (RDN) with high level of PV penetration. The strategy is based on the capability of PV inverters in terms reactive

power support (RPS). In accordance, a volt/var (Q-V) management technique is proposed and tested on various R/X ratios. The following conclusion can be made based on the research analysis:

- The active power of PVs needs to be reduced to maintain the system voltage under permissible limits, either by active curtailment or through storing the excess active PV power in an energy storage systems.
- It has been observed that the feasibility of RPS by the inverter is dependent on the R/X ratios of the RDN.
- A significant amount of line losses are incurred if the R/X ratio is high, thereby limiting the scope inverter RPS.
- The proposed control active-reactive power management strategy suitably maintain the voltage under permissible limits in urban area and the hosting capacity of the network for renewable penetration can be significantly increased.
- In case of rural scenario, energy storage systems are required to further support voltage regulation as high R/X ratios introduce higher degree of voltage fluctuation.

5.0.1 Future Work

Energy storage system will undoubtedly play a vital role towards renewable and sustainable development in the energy sector. Considering various technological

constraints of each storage technologies, selection of a viable storage technology based on local conditions are inherently pertinent. Research work based on environmental, topological and technical characteristics is severely lacking. Therefore, based our analysis, the future work of storage technologies are:

- Saudi Arabia has the topological sites for pumped storage technologies, a comparative and economical analysis between vanadium redox and pumped storage technologies is needed to conclude the techno-economic superiority between these two technologies.
- A feasibility test to identify the hybridization of vanadium redox battery (VRFB) with supercapacitors or other technologies. Since power density of VRFB is very low.
- Identification of storage technologies based on their characteristics is required to selectively categorize them with respect to the challenges and requirements associated with renewable integration.

Similarly, numerous area of research needs to be addressed to quantify the applicative scope of hybrid battery-supercapacitor energy storage system.

- Limited work has been presented to enumerate the potential capability of BESS-SCSS-HESS in terms of inertial support and primary frequency control, which might be the key factor to quantify its permissibility in black-start process of, distributed generation systems.
- Extensive research has been done considering solar and wind power as en-

ergy sources, however, implementation of BESS-SCSS in ocean wave energy extraction is severely lacking to identify its applicative scope in marine technology.

- Finally, the application in wireless power transfer that enhances the runtime and voltage profile of the wireless nodes has research potential to be implemented in wireless PV, EV and biomedical devices but the research work performed is highly insufficient to conclude its viability in these fields.

Finally, the future scope of the presented solutions for voltage regulation at various stages of RES integration, especially at high PV penetrations are as follows:

- The effect of reactive power capability in the field of optimal sizing and placement of solar PV.
- Study of the reactive power capability with more complex transient variability of PV power production, and
- Integration of hybrid energy storage systems with PV inverters.

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