AUTONOMOUS CHARGING MANAGEMENT OF ELECTRIC VEHICLE

BY

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عمادة الدراسات العليا
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This thesis is dedicated to my beloved parents and sisters.

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LIST OF ABBREVIATIONS

BEV	Battery Electric Vehicles
DG	Distributed Generation
ECT	End of Charge Time
EV	Electric Vehicles
FCEV	Fuel Cell Electric Vehicles
HEV	Hybrid Electric Vehicles
ICE	Internal Combustion Engine
ITS	Intelligent Transportation System
PD	Power Draw
POC	Point of Charge
SC	Shunt Capacitor
SOC	State of Charge
TOU	Time of Use
VR	Voltage Regulator
V2G	Vehicle to Grid
WT	Wind Turbine

ABSTRACT

Full Name [Samy Gamal Faddel Mohamed]

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Increased concerns of environmental problems, depletion of fossil fuel and the increased use of renewable energy resources in power grids are all factors that are increasing the focus on Electric Vehicles. It was reported that ‘‘Fast-charging’’ a vehicle battery at 4 kW on a low voltage grid is equivalent to adding many times the average US household’s instantaneous power load. So, the effects of peak-demand could be a risk to the grid if all vehicles were to charge at the same time. Many studies showed that without any management over the charging, failures or unacceptable electricity quality will occur in the grid frequently even with a small EV penetration rate. So, charging management is a major concern for successful integration of electric vehicles in the distribution network.

In this work, a voltage-feedback-based technique with variable gain is introduced to manage electric vehicle charging. This control strategy requires no communications from the utility whatsoever as the controller’s only input signal is the local nodal voltage at the charging point. The proposed control method ensures not only that the distribution feeder voltages will never vary outside of voltage limits set by the respective distribution system but also a fair charging among the different electric vehicles at different nodes of the system. Also, several of the practical considerations on the distribution system are addressed. These include different loading conditions, system reconfiguration, and end-of-charge time preference. Voltage control devices in the system are considered to ensure

proper interaction between the proposed controller and the existing control unit in the system. Moreover, the controller behavior in the presence of distributed generation units such as wind turbines is studied. The simulation results show that this method can successfully reduce EV charging to eliminate system voltage violations that would otherwise be caused from EV charging while ensuring fairness among the various EVs. Also, there is no need for updating the voltage set points due to seasonal variations.

In addition, these results demonstrate the effectiveness of the proposed approach in the presence of other voltage control devices in the system as well as distributed generation units.

ملخص الرسالة

الاسم الكامل سامى جمال فاضل محمد

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التخصص الهندسة الكهربية

تاريخ الدرجة العلمية مايو ٢٠١٥

لقد أدى الإهتمام بمشاكل البيئة و توقعات نفاذ الوقود الأحفورى إضافة إلى زيادة استخدام مصادر الطاقة المتجددة فى الشبكات الكهربية إلى زيادة التركيز على السيارات الكهربية، حيث بينت الأبحاث أن الشحن السريع لتلك السيارات من شبكة الجهد المنخفض بمعدل ٤ كيلواوت يعادل عدة مرات الطاقة اللحظية المستهلكة لمتوسط البيت الأمريكى مما قد ينتج عنه خطورة زيادة أحمال الذروة لو حدث أن كل السيارات شحنت فى نفس اللحظة. ولقد بينت العديد من الدراسات أنه بدون إدارة عملية الشحن تلك فإنه قد تحدث مشاكل فى جودة الطاقة أو حتى إنقطاعات فى الكهرباء حتى ولو كان عدد السيارات الكهربية المتصلة بالشبكة قليلا ولذلك تعد عملية إدارة الشحن أمرا هاما للحصول على اتصال ناجح وزيادة عدد السيارات الكهربية المتصلة بشبكة التوزيع الكهربية.

فى هذا العمل البحثى يتم تطوير تقنية إدارة شحن تعتمد على التغذية الإسترجاعية للجهد حيث يتم التحكم فى عملية الشحن بعد ذلك عن طريق تكبير فرق الجهد بمعدل متغير إعتمادا على قيمة فرق الجهد نفسها، ولا تتطلب عملية التحكم تلك أية وسيلة إتصال بين مشغل الشبكة والمتحكم فى السيارة الكهربية حيث إشارة الدخل الوحيد هى قيمة الجهد عند مدخل الكهرباء الذى يتم الشحن منه، ولا تضمن تلك التقنية عدم تغير الجهد خارج القيم القياسية للشبكة الكهربية فقط ولكن تضمن أيضا عدالة الشحن بين السيارات المختلفة المتصلة بالشبكة الكهربية. ولقد تم الأخذ فى الإعتبار العديد من النقاط العملية المثارة مثل حالة تغيير قيم الأحمال الكهربية المتصلة بالشبكة أو التغيرات التى قد تحدث فى شكل توصيل الشبكة الكهربية وكذلك تم أخذ إرادة صاحب السيارة الكهربية فى حالة إذا ما أراد شحن السيارة فى عدد معين من الساعات.

إضافة لذلك تم دراسة التقنية المقترحة فى حالة وجود أجهزة تحسين جهد متصلة بالشبكة الكهربية كما تم الأخذ فى الإعتبار دراسة سلوك التقنية فى حالة وجود أنظمة توليد موزعة مثل توربينات الرياح، ولقد أكدت النتائج أن التقنية

المقترحة تمنع أى خرق للمعايير القياسية للجهد كما تضمن عدالة فى الشحن بين السيارات الكهربية المختلفة. كما بينت أيضا أنه ليس هناك حاجة لتحديث قيم الجهد المستخدمة للمقارنة فى التحكم بالتغير بين الفصول المختلفة فضلا عن الأداء الجيد للتقنية فى وجود أجهزة تحسين الجهد ووحدات التوليد الموزعة.

CHAPTER 1

INTRODUCTION

1.1 Background

The increased concerns of global warming and the rising of Kyoto Protocol emerged in 1997 accompanied with fossil fuel depletion and increased interest in deployment of renewable energy resources lead to increased interest in electric vehicles. EVs have many positive benefits, such as reduced local emissions and petroleum independence. However, their charging can have adverse effects on the grid. While problems on the bulk power system are possible for large numbers of EVs [1], impacts on the distribution system are expected to be significant [2]. The charging of these EVs can be a relatively large load in the distribution grid. Many studies showed that without any management over the process, failures or unacceptable power supply quality will occur in the grid frequently even with a small EV penetration rate [3], [4]. The resulting impacts, on the low voltage distribution grid range from transformers overloading [5] to harmonics [6] , low voltage, and phase unbalance [7]. Therefore, charging management is a major issue for successful integration of EVs in the distribution network.

1.2 Thesis Motivation

Due to the increasing interest in EV and the expected wide deployment of it, impacts on the distribution system are expected to be greatly high. Impacts can range from line overloading in both primary and secondary distribution systems to under voltage problems and transformer overloading. Under voltage problem is expected to be the limiting factor against integrating large number of EVs. Many management schemes have been introduced to control the charging of EVs in the distribution system to avoid voltage violations and overloading problems.

Management schemes for EV charging can be classified into three major schemes as centralized, decentralized and autonomous control strategies. The centralized strategy provides voltage regulation from the substation to the rest of the network, potentially including a wide deployment of communication systems to coordinate different devices (Capacitor banks, voltage regulators, etc.) [8], [9]. The decentralized one provides charge management using less communication system where communication only occurs within small area (i.e. parking lot only). The autonomous control strategies are, on the other hand, aimed at locally controlling the electric vehicle in an active way [10]–[15] with no need for communication at all. The autonomous control strategies can improve the overall network performance while limiting the need for large investment on communication system infrastructure.

In this work, a voltage-feedback-based technique for EV charge management with variable gain is introduced to manage electric vehicle charging. This control strategy requires no communications from the utility whatsoever as the controller's only input signal is the local nodal voltage at the charging point. The proposed control method ensures not only that the distribution feeder voltages will never vary outside of voltage limits set by the respective distribution system but also a fair charging among the different electric vehicles at different nodes of the system.

The only input to the controller is the nodal voltage, which is measured locally. Based on this input and other considerations, the controller decides on the charging rate for the EV. The strategy will be tested on a realistic distribution network.

1.3 Thesis Objectives

In this thesis, a fair strategy to ensure fair charging between the down and upstream points without voltage violation is proposed. A variable gain based on the nodal voltage will be used instead of the constant gain used in the previous work [16]. Also constant reference voltages will be used instead of the different ones used before. The main advantage of constant reference voltage points is that it removes the need to update the setting point due to seasonal variation or system reconfiguration which is common in power system. Also, the use of variable gain controller, based on local voltage measurement, provides flexibility of charging and increase the charging rate whenever there is a room for charging like cases of light loading in late night. So, the following objectives have been selected which will serve as a contribution of this thesis:

1. To design a practical voltage based EV charge control strategy. Several of the practical considerations on the distribution system will be addressed. These include different loading conditions, system reconfiguration, and end-of-charge time preference.

2. To ensure proper interaction between the proposed control strategy and existing voltage control devices in the distribution system.
3. To study the controller behavior in the presence of distributed generation units.
4. To study the effectiveness of the proposed EV charge control algorithm through simulation considering detailed modeling of the distribution secondary system.

1.4 Thesis Organization

The thesis is organized as follows:

Chapter 2 gives a general overview of the different types of vehicles and the differences among them as well as literature review about the recent publications tackling charging management problem.

Chapter 3 introduces the proposed control technique as well as the test system and the different assumptions that are used.

Chapter 4 presents simulation results with comparisons among 3 different charging methods.

Chapter 5 shows performance analyses of the proposed control scheme.

Chapter 6 presents the effectiveness of the proposed technique in the presence of voltage control units such as capacitor banks.

Chapter 7 shows the behavior of the controller in the presence of distributed generations.

Chapter 8 shows conclusion and future work.

CHAPTER 2

OVERVIEW OF ELECTRIC VEHICLES

2.1 Historical Background of Electric Vehicles

At the turn of the 20th century the automobile began to dominate transportation, with three types of vehicles competing for market share steam powered engines, internal combustion engines (ICEs) and electric vehicles (EVs). Initially, electric vehicles fared well in comparison to competitors, with a smooth, quiet ride, no tailpipe emissions, and relatively reliable starting compensating for higher expense. In 1904, EVs held about one-third of the market share in New York, Chicago, and Boston. One of the other main competitors, the horse-drawn carriage, was prevalent at the time in large cities but residents were increasingly critical of drawbacks such as manure that dirtied streets and was unpleasant for obvious reasons. Further, the ICE's loud, polluting engine seemed to be an unsatisfactory alternative next to the EV's relatively quiet, smog-free ride [17].

A core market was created for EVs when in 1896. New York City began turning to electrics to replace horse-drawn carriages to be used as taxis. The Electric Vehicle Company in New York began producing electric vehicles, called the "Electrobat," and they were, by-and-large, a success. About sixty Electrobats were in service by 1899, by then a second version, the Electrobat II. These vehicles would replace their batteries with a fully charged one at designated switching stations every four hours.

Despite a general acceptance with the public, EVs faced several drawbacks still largely present today, including relatively short range and lack of knowledge over how to maintain the vehicles. Further, "convenient, cost-effective charging stations beyond the major population centers had been an issue from the beginning for electrics". Because of these drawbacks, ICEs became much more attractive in comparison when an electric starter was invented in 1912, replacing a difficult to operate and often dangerous crank starter [17]. With ICEs, easy to start and EVs limited distance per battery charge, the EV was fast becoming a niche market.

2.2 Types of Electric Vehicles

There are three main types of current electric vehicles which are competing for the future market share. The three electric vehicles are Hybrid Electric Vehicles (HEV), Battery Electric vehicle (BEV) and Fuel Cell Electric Vehicle (FCEV). HEV and BEV have the advantage of using their electric motor as an energy generator through regenerative braking and as a form of frictionless braking. FCEVs can allow for regenerative breaking if a battery is used to assist the fuel cell. When only considering plug-in electric vehicles (PEV; electric vehicles whose batteries can be charged by plugging into the electricity grid), vehicles can be divided into battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEVs) [18].

Brief description of the different types of vehicles as follow:

2.2.1 Battery Electric Vehicles

A Battery Electric Vehicles (BEVs) is propelled by one or more electric motors and only use the power provided by its on-board battery for propulsion. The large battery is charged from the electricity grid and the power train is simple by design. Benefits include the absence of tank- to- wheel emissions, high energy efficiency, as well as much less operating noise; technical disadvantages include a relatively low achievable range and the long time required for charging the batteries because their low energy density. Their motors can produce great torque at low speeds and are generally three times more efficient than internal combustion engines. BEVs have much fewer moving parts than internal combustion engines vehicles and do not need regular oil changes. Typical ranges for freight BEVs vary from 100 to 150 kilometers on a single charge but have been reported to diminish over time due to battery ageing [18].

2.2.2 Hybrid Electric Vehicles

Hybrid electric vehicles (HEVs) combine an internal combustion engine and an electric motor. They can either be classified according to their power train architecture (series, parallel, series-parallel and complex), the level of electric power and function of the electric motor (micro hybrid, mild hybrid, full hybrid) or their capacity to be plugged into the electricity grid to recharge their batteries. In series configuration, the internal combustion engine (ICE) is only used to power a generator and the electric motors is the only propulsion component coupled to the final drive shaft, while parallel configuration allows for both the ICE and the electric motor to be coupled to the final drive shaft and to be used simultaneously or individually. A plug-in hybrid electric vehicle (PHEV) is essentially an HEV with a larger battery which can be charged from the electricity grid. PHEVs could be a viable transition technology as it allows short trips to be made in electric mode and alternative fuels to be used for longer itineraries [18].

2.2.3 Fuel Cell Electric Vehicles

In an Fuel Cell Electric Vehicles (FCEVs), a fuel cell generates electricity from hydrogen`s chemical energy, from which the output is water; then it either powers the electric motor or charges the battery. Fuel cells are electric generation devices, while batteries are electric storage devices. A battery can be used in an FCEV to store the electric motor`s regenerative braking energy and to assist the fuel cell during sudden load variations that it cannot handle by itself. The hydrogen must be stored on-board either in gaseous or liquid states or through physical or chemical adsorption. FCEVs also offer quiet operation thanks to few moving parts, but are less efficient than BEVs since the fuel cell must convert the hydrogen`s energy into electricity before powering the electric motor. Nevertheless, they are more efficient than internal combustion engines electric vehicles and fuel cell efficiencies are approximately 50% in terms of the proportion of hydrogen`s energy being converted to electricity. FCEVs can be refueled in few minutes and can achieve ranges several hundred kilometers using compressed gaseous hydrogen storage tanks. The cost of FCEVs is still an important market barrier for this technology. Another significant barrier is fuel cell durability, which is currently 10000 operating hours at best [18].

2.3 Transportation Systems and Smart Grids

Smart grids will be the future energy system that will have a great impact on both future society and economy. The integration between transportation systems and smart grid is expected to happen in multiple dimensions. Initiated by the IEEE Standards Association, the IEEE Smart Grid (SG) Vision is intended to be a long-term vision of what the SG will look like 20 to 30 years from now. In the Transportation Systems (TS) society, the SG Vision for Vehicular Technologies Project was kicked off in mid 2011. The joint forces of technological leaders with diverse expertise related to TS and SG have resulted in the creation of a rich set of forward looking use cases, application scenarios, and corresponding enabling technologies for future SG–TS integration [19]. The foremost interface between the SG and the TS consists of vehicle-charging units, which offer assurance for users and flexibility for the utility. Their networked intelligence will enable more efficient and effective vehicle–grid systems, but will most likely require bidirectional battery chargers. Incorporation of this foremost interface, however, urgently calls for the development of an integrated smart infrastructure; the challenge lies in the assurance of synchronized energy flow, transportation flow, and communication flow. Adapting to such macro-scale development, individual travelers' role will also evolve rapidly from the traditional picture Travelers as mobile nodes will be able to optimize their route/time schedules in a multidimensional grid based on considerations including energy, travel time, environmental impact, and data connectivity [19]. To achieve the after mentioned targets, a massive coordination between the transportation system and the smart grid will be required. As with any technological innovation, the vehicle–grid technologies and systems will greatly affect the economy and society. Figure 2-1 shows the future intelligent transportation system.

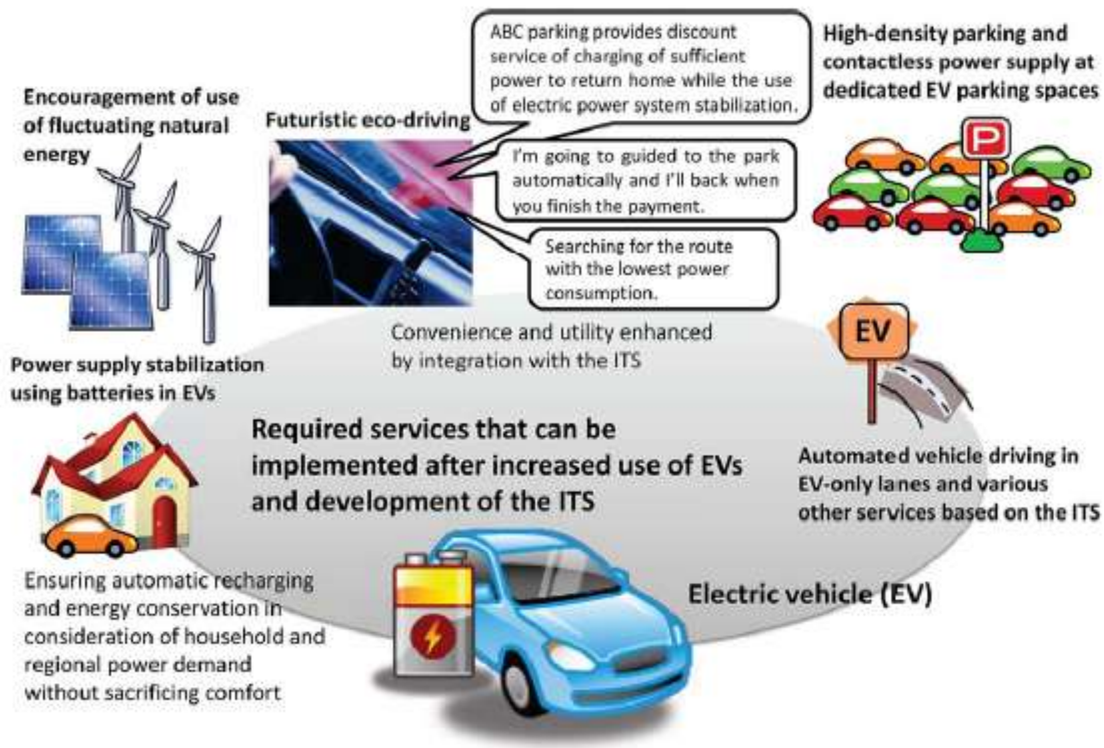

Figure 2- 1 Example of future intelligent transportation system [19]

2.3.1 Electric Vehicles in Intelligent Transportation Systems

Battery electric vehicles nowadays have the advantage of using their electric motors as an energy generator through regenerative braking and as a form of frictionless braking. For future EVs, an intelligent vehicle-charging unit will play much more critical roles for these purposes. From the user perspective, it offers assurance about when a battery pack is fully charged and ready, and includes diagnostics to monitor the vehicle and the battery. It can manage the timing of charge in a manner that reduces energy cost, optimizes battery life, and maintains safe conditions. From the utility perspective, it offers flexibility. A vehicle is parked most of the time, and the timing of a charge process can be adjusted if that provides benefits. It can serve as an energy storage resource to the grid, or it can interact more directly with a time-varying renewable resource such as wind or solar power [19].

One of the key issues for electric vehicles is the management of their utility interaction. It is well established that uncontrolled on-demand battery charging turns vehicles into uncontrolled loads on the grid and will cause unacceptable voltage drops and overloading the distribution system equipments. Several studies suggest substantial life reduction in grid transformers and reduced customer reliability when charging is not subject to control. However, there is a good reason to expect that consumers will be motivated to take advantage of controlled charging. In many systems, for example, the ratio of peak daytime electricity prices to late night prices is four to one, six to one, or even more. Even during the day, real-time prices tend to be the highest during just one or two hours; therefore, even limited flexibility can lead to noticeable economic benefits. Consumers are likely to take advantage of low off-peak and controllable electricity prices, provided two conditions are met:

1. The charger that interacts with the vehicle is highly automated and easy to set up;
2. The consumer is able to invoke an energy guarantee, by which a battery pack will be assured of a certain target energy state no later than a specified target time.

An intelligent plug-in vehicle acts as an "energy load," in the sense that the typical requirement is for a specific amount of energy, but to be delivered over a relatively flexible time interval (e.g., "provide 10 kWh total no later than 600 A.M. tomorrow"). Energy loads are relatively rare in residential systems but are actually fairly typical on the supply side, where the concept is common for large-scale energy exchange (e.g., "deliver

200 MWh between 2:00 P.M. and 4:00 P.M. next Tuesday") [19]. The implication of both conditions is that an intelligent plug-in vehicle, although a significant consumer of energy, can sell flexibility to the grid operator [20].

2.4 Current and Future Vehicles Market Share

Demand for fuel for conventional vehicles, which is met nearly exclusively from oil, is expected to rise slowly over the next decade before gradually trending downward over the remainder of ExxonMobil outlook up to 2040. This shift in demand won't be because of fewer vehicles in the world. In fact, from 2010 to 2040, the number of light-duty vehicles is expected to be more than double from about 800 million to about 1.7 billion, as the world's population grows and more people in developing economies are able to afford cars. Importantly, the increase in the number of light-duty vehicles in the world through 2040 will likely be nearly offset by the fact that the vehicles themselves will be far more fuel efficient. As a result, the average efficiency of the world's vehicle fleet is projected to reach about 46 mpg (about 5.1 liters per 100 km) compared to 24 mpg (9.8 liters per 100 km) in 2010. This unprecedented improvement in global fuel economy is expected to reflect a surge in hybrid vehicle sales. Hybrids, which combine an internal combustion engine and an electric motor, are expected to account for about half of global new-car sales by 2040, as they become increasingly cost competitive compared to conventional vehicles. By 2040, hybrids are expected to account for about 35 percent of the global light-duty vehicle fleet, up from less than 1 percent in 2010. Over the same period, electric and plug-in vehicles are expected to grow to about 70 million cars, or less than 5 percent of the total fleet [21] . Figure 2-2 shows the expected number of light fleet vehicles by type up to 2040.

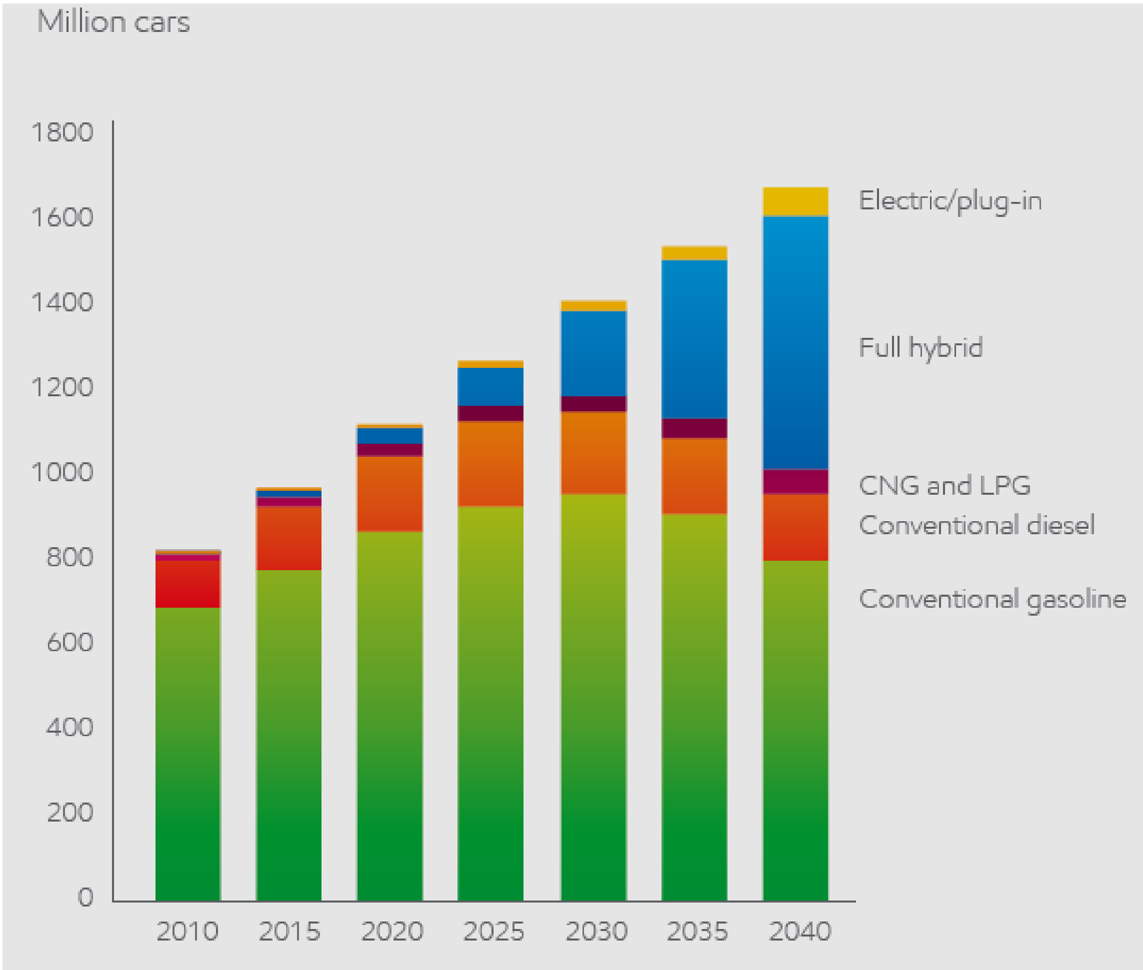

Figure 2- 2 Light duty fleet by type [21]

2.5 Literature Review

Electric vehicles are attracting greater attention and expectation since they are environment-friendly and a cost-effective solution for fuel economy. This is because electricity costs about \$0.03 per mile (at\$0.13/kWh) where as gasoline costs \$0.12/mile (at\$3/gallon) [22]. Forecasts of vehicles worldwide show that by 2040, hybrid EVs are expected to account for about 35 percent of the global light-duty vehicle fleet, up from less than one percent in 2010. Over the same period, electric and plug-in vehicles are expected to grow to about 70 million cars. Slower growth of electric vehicles is attributed to the relatively higher cost of the vehicles, driven by the cost of batteries [23] , but this cost is expected to be greatly reduced after the commercial releasing of the new batteries types. These new batteries have a longer life time up to 20 years, hence the customer will no longer need to replace the batteries each five years, and this will save $5000 the user was supposed to pay each five years. The Ministry of Economy, Trade and Industry (METI) of Japan has announced a policy named "Next-Generation Vehicle Strategy 2010", in which a target of introducing of domestic EV and plug in hybrid EV was made 20~30% in 2030. In a survey for consumer preference for electric vehicles, two-thirds of consumers surveyed stated that EVs have unique features that stand out from their gasoline counterparts [24] . But integrating large number of EVs to the utility will cause some problems. While problems on the bulk power system are possible for large numbers of EVs [25], impacts on the distribution system are expected to be more significant. These impacts may include voltage sag, load peaking and increased losses. However, it was shown that with adequate management, the negative impacts of EVs can be reduced and the penetration depth of electric vehicles can be increased [26].

Several ways have been proposed in order to control EV charging to prevent negative impacts on the utility grid. These methods can be broken into centralized charging control, decentralized control and autonomous charging control.

2.5.1 Centralized Charging Control

Many methods of EV charge management have focused on centralized scheduling and control [27], [28]. Various methods of minimizing distribution feeder losses were explored. These studies revealed that feeder load profile can be flattened, voltage violations can be reduced [27], [29] and transformer life can be extended [5]. All of these methods required feeder load forecasts. In [28], [30] economic based charge control was investigated. It was found that price-based methods can sometimes cause distribution system overloads in the night hours due to low system prices but loss optimization would always flatten the load profile as much as possible. The method require good communication infrastructure to perform well. In [26], the centralized control strategy allowed balancing single-phase loads connected to the microgrid by adapting the charging rates of the EV storage devices. While in [31], The authors showed three scenarios using Monte Carlo simulation and indicated the permissible penetration of electric vehicle for normal operation with no control, with the proposed PQ inverter control and the case of using communication between the EVs and distribution system operator. They showed that the proposed algorithm can increase the number of EVs in the grid without voltage violation and with communication, it can increase even more.

Three approaches were studied in [32]; dumb charging, dual tariff policy and smart charging. Voltage profiles and lines congestion levels were evaluated, for the peak load hour, for grid technical limits checking. Also network Losses were evaluated for a typical daily load profile. Smart charging with hierarchical centralized control showed the best performance and it showed that voltage is the limiting factor for higher integration of EVs.

Communication with the transformer substation for the sake of fair charging of electric vehicles as soon as possible was investigate in [33]. The connection rate of EVs keeps increasing until the set point limit is reached and then it varies up and down to maintain the set point level. At the end of each minute interval, the EV chargers will again attempt to connect with the connection rate probability. The random process used for connecting the electric vehicles ensures that each of the EVs has a fair access to the available power. In [34], the authors proposed a centralized charging control that allows the EVs to find, via a distributed communication network either the closest charging station, and then only be allowed to charge if there are no network constraints, or the charging station that will allow for the quickest charge. Electric vehicles on large scale were used to provide frequency regulation (FR) in the utility grid in [35] in which the authors presented a coordinated control strategy for large-scale EVs, BESSs (Battery Energy Storage Station) and traditional FR resources involved in AGC. It was shown that EVs and BESS can provide fast response in case of disturbance of short periods but if the disturbance continued for longer period, only the AGC will participate in the response continuously.

In [36] the effect of EVs in providing ancillary services with wind integration was investigated. It was shown that the regulation power requirements from conventional generators were greatly reduced with the integration of a V2G system participating in load frequency control. In [37], V2G algorithm is developed to optimize energy and ancillary services scheduling. An optimal bidding formulation for EVs performing regulation up and down with only unidirectional power flow was developed. The simulations were performed on a simulated market with constant prices of regulation services over the study year. None of the V2G studies, however, address examine charging impacts on the distribution system and they require significant communications bandwidth to dispatch the EVs so frequently. Additionally, the optimization requires significant computational power by the centralized controller. In [38],[39] the authors used a coordinated voltage controller to actively integrate a high share of renewable into existing distribution systems. PLC (Power Line Communication) and radio link systems were used to enable communication between the centrally operated voltage control unit and DGs via tele-control protocol. The voltage control algorithm used for controlling the voltage by optimal orchestration of the DG's reactive power injection and consumption, as well as the tap position of the OLTC.

All of these methods require well-developed communication infrastructure to dispatch the control commands to and from the EVs.

2.5.2 Decentralized Charging Control

Some other methods have focused on decentralized control and optimization of EV charging, which requires reduced communications infrastructure and computational burden. In [10] , the coordination of EVs was performed using non-cooperative games to minimize generation cost. A distributed algorithm that considers the EV battery state of charge (SOC) was proposed in [13] to level the load at night. The algorithm presented in [40] was based on EVs setting their own charge profiles according to price forecasts. Another decentralized method focused on managing all of the charging within a parking lot while the parking lot was given its own maximum charge rate [41]. In [42], a distributed framework was suggested that aims to have EVs to charge at comparable charging rates without overloading the upstream service transformer.

In [43], large population of plug in electric vehicles was used to mitigate wind intermittency and frequency regulation. Each PEV adjusts its charging or discharging power in response to a communal virtual price signal and based on its own urgency level of charging. The proposed scheme created cost saving opportunity for both PEV owner and the utility. In [44], A pricing scheme that conveys price and quantity information to the load aggregator (LA) was developed and compared with the pricing only scheme. It was shown that the price/quantity scheme is insensitive to the regularization penalty and requires less computation capability than the pricing only scheme. However the pricing scheme was to minimize the charging costs for the PEV owner. If the objective was changed to profit maximizing for the utility, the method loses its beneficial properties.

In [45], control of energy flow between EVs and the grid has been demonstrated using fuzzy logic controllers (FLC) mainly for voltage compensation and peak shaving. The proposed technique suggested uses heavy computation and assumes that the customers` EVs are available to be charged and discharged neglecting the effect of these V2G on the battery life time. It also assumes that all EVs in a certain area will charge from a certain charging station and the charging station will work most likely as an aggregator. In [46], the effectiveness of distributed additive increase and multiplicative decrease (AIMD) charging algorithms at mitigating the impact of domestic charging of EVs on low-voltage distribution networks was investigated. The method proposed tries to achieve fair charging between different vehicles without violating the voltage constraint or overloading the substation and at the same time it took into consideration, the time of use prices. To achieve the mentioned objectives, they used a simple radial communication between the distribution station and the vehicles.

These and other similar decentralized charging methods rely on communications from the utility of some sort, even if there is no communication from the EVs back to the grid.

2.5.3 Autonomous Charging Control

A few communication-free EV charging strategies have been developed to allow autonomous charge control. In [47], voltage-constrained local optimization of EV charging was suggested. Each EV in the system optimizes its own charging aiming to maximize its charging rate while not violating nodal voltage or feeder loading constraints. This paper suggests a localized voltage-aware charge strategy of a competitive nature. However, it does not consider charging fairness and battery SOC of each EV. Comparable performance can be obtained using simpler control structures. Lopes et al. [26] introduced a voltage-feedback, frequency-feedback control structure for bi-directional V2G within a microgrid. The results showed the effectiveness of this structure in preventing voltage and frequency violations. A voltage-feedback control structure for EVs in a distribution system was shown in [48]. However, the issue of fairness among EVs connected to different nodes in the system was not addressed in [26], [48]. SOC dependency of charging rate was not considered, either. In [49], EVs contributes to frequency regulation and spinning reserve triggered by self-terminal frequency signal. The suggested scheme also took into consideration charging request for the next drive and battery condition during the vehicle to grid, but the issue of fairness among EVs connected to different nodes in the system was not addressed.

An autonomous control scheme for multiple electric vehicles in the distribution network was proposed in [50]. The proposed method focused on using the electric vehicle as energy storage during transition from grid connected mode to islanded operation.

The control just relies on local measurements of voltage and currents. The penetration depth considered in the residential area is small since only 3 vehicles were considered; the fairness of vehicle charging over long time period was not investigated and the effect of set points of control charging was not also investigated.

In [51], the authors propose an active power/ frequency (P - f) droop control strategy to be implemented at the EV coupling inverter where the EV will autonomously adapt its power output based on the microgrid (MG) frequency. The drawback of this method is that it did not take voltage violation into consideration. In [52], the authors addressed autonomous approach for real time management of local voltage, utilizing the concept of sensitivity analysis. Results from time-series analyses reveal its effectiveness in managing constraints. But, it requires a complex algorithm and reliable data exchange between DGs and loads.

In [53], two electric vehicle charging algorithms were proposed, one centralized and one distributed, and their performance in simulations that used real vehicle data were compared, on a model based on a real LV network in northern Melbourne, Australia. The algorithm proposed for distributed charging uses probability criteria to decide whether the vehicle will be charged or not. This probability is based on the node voltage and SOC of the EV`s battery. It does not take into consideration the charging rate. Also the method used can be used only up to 25% penetration level and it`s sensitive to the location of vehicles in the network; when vehicles are connected near the far ends of the network, there is a significantly increased risk of voltage drop.

The authors in [54] proposed a method that uses only local information which are the node voltage and SOC and based on that information and time of required charging given by the user, the algorithm controls the charging rate. It uses averaging technique method to find the set point voltages used in control which mainly depends on historical data. The problem of fairness was not completely proved in the results. In [55] the author has proposed an effective, autonomous, voltage-based control scheme for charging electric vehicles. This control scheme, though requires no real-time communication, effectively coordinates charging among the EVs connected to the distribution nodes in a fair manner so that voltage violations are avoided. The proposed method use a constant gain values and the upstream point charges faster than the downstream one. In [16], The author developed a communication free i.e. an autonomous voltage feedback control structure, for EV charging based on the model in [55] . This control structure relies on the local voltage measurement at the point where EV is plugged in. It compares the system measured voltage at the point of charging with a predefined reference voltage. The drawback of the proposed algorithm is that; it needs to update the set points with each seasonal variation, and the upstream point charges relatively faster than the downstream one. Also, coordinating the proposed voltage controller with the distributed generation units was not performed.

2.6 Outcome of Literature Review

It can be seen from the literature that so much work has focused on centralized control algorithms. However, all of these methods require well-developed communication infrastructure to dispatch the control commands to and from the EVs. Also, they require a powerful computation system to handle the large amount data from different elements in the system. The literature for decentralized control has shown that most decentralized charging methods rely on communications from the utility of some sort, even if there is no communication from the EVs back to the grid. So, in both ways, centralized and decentralized methods, a significant investment is required to develop the communication infrastructure required for proper operation.

For the autonomous charging control, although researchers have started working on developing a localized charging algorithm, a few papers have been published and there are still many gaps to be filled, and a lot of issues need to be addressed in order to convince its real time usage from the perspective of both distribution companies and EV owners. Some of these gaps are the sensitivity of the charging of the EV to its location, The EV owner end of charge time preference and behavior of EVs charging in case of reconfiguration of the distribution system.

CHAPTER 3

TEST SYSTEM AND VOLTAGE BASED FEEDBACK CONTROLLER

3.1 Test System

The primary distribution test system used for simulating the EV charging impacts is shown in Figure 3-1. This is an unbalanced three phase system with 17 load buses. This system was originally introduced in [56], and was one of the systems used to study EV charging impacts in [27]. It has also been used in microgrid studies [57]. The primary distribution system operates at a nominal 12.47 kV line-to-line voltage. The conductors are organized in a symmetric geometry with a geometric mean spacing of 4.69 ft. Every load bus has 20 houses connected to each secondary phase. The load profile for each house is based on Residential High Winter Ratio (ResHiWR) load profiles on July 20, 2010 found in the ERCOT (Electric Reliability Council of Texas) system with five minute resolution [58]. To the base load profile, normally distributed random noise is added to model variations in individual usage. The parameters of the distribution system are found in Table 3-1. The secondary distribution system is modeled based on the field site configuration of Utility E in [59], which has several splice boxes as well as houses connected directly to the distribution transformer through triplex lines at a nominal service voltage of 240 V as shown in Figure 3.2. The parameters of the secondary distribution network are given in Table 3-2. A small resistance is also added to model the EV charging cable.

An average of one EV per two houses in the system, i.e. a 50% penetration level, is assumed. Each EV is randomly assigned to a house on the secondary network. This level is chosen because it has been shown to cause significant problems with EV charging [27]. Each EV has a maximum charge rate of 6.6 kW and needs to charge 24 kWh to reach full capacity. This corresponds to a 2013 Nissan Leaf [60]. Average initial state of charge of each EV is assumed to be about 40% of the battery's full capacity. In addition, it is assumed that 10% of the EV owners have preferred ECTs (End of Charge Times), which range between 4 and 7 hours. These have also been assigned randomly.

It is assumed that the system under study is under a time-of-use (TOU) tariff structure. A lower tariff is applied from 7 pm to 7 am. Therefore, it is expected that the majority of EV owners plug in their EVs at or after 7 pm. To take this into account and the fact that EV plug-in time is expected to be random, the EV plug-in time is assumed to follow a Gaussian distribution centered at 8 pm and with a standard deviation of one hour.

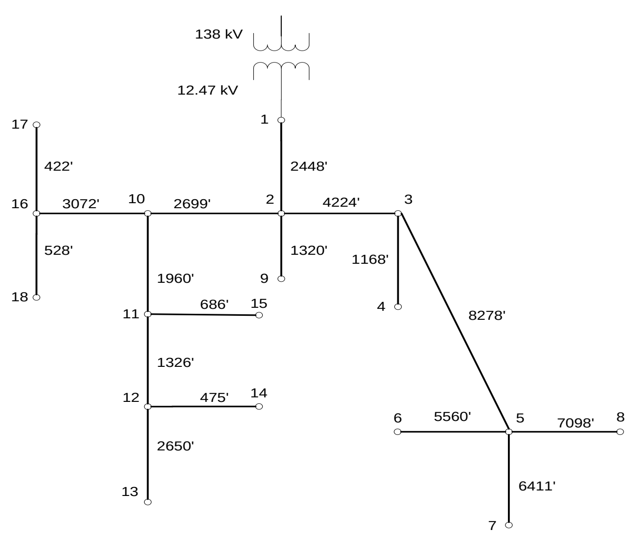

Figure 3- 1 The distribution feeder test system. Load buses are 2-18

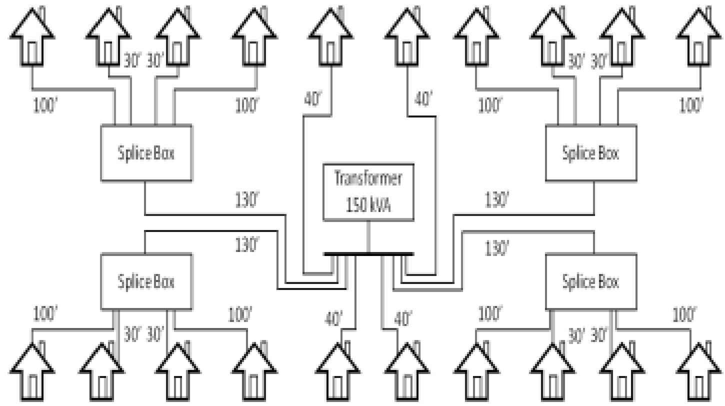

Figure 3- 2 Secondary distribution network topology

Table 3- 1 Distribution System Parameters

Phase Conductor	ACSR 2
Neutral Conductor	ACSR 4
Max Amps	180
Houses	1020

Table 3- 2 Secondary Network Parameters

Parameter	**Value**
EV Charger Penetration	50%
Distribution Service Transformer	150 kVA, %Z = 1.8
Secondary Conductor (transformer to splice box)	350 Al, 4/0 Al Neutral
Service Conductor (to the houses)	#2 Al
No. of customers	20

Figure 3-3 shows a basic schematic diagram of the simulation setup designed in the Matlab/Simulink environment. Three phase power flow is used to do load flow analysis to calculate the voltages at different charging points of the system. The load flow uses forward-backward sweeping algorithm which is commonly used for radial distribution systems. The inputs to the load flow are the total power at points of charging and the outputs of the three-phase power flow block are the voltages at the points of charging, i.e. at the houses. Here, n represents the node number, where $n \in [2, 18]$, p is the phase number, where $p \in [1, 3]$, and i is the house number, where $i \in [1, 20]$. The voltage of each house (V_i) is fed back to the EV charge controller at that house to be compared with a reference value ($V_{ref,i}$). The controller decides on the power draw, *PD(n,p,i)*, which is added to the non-EV load at the house, and the total power, *P(n,p,i)* is used as an input for the next power flow update.

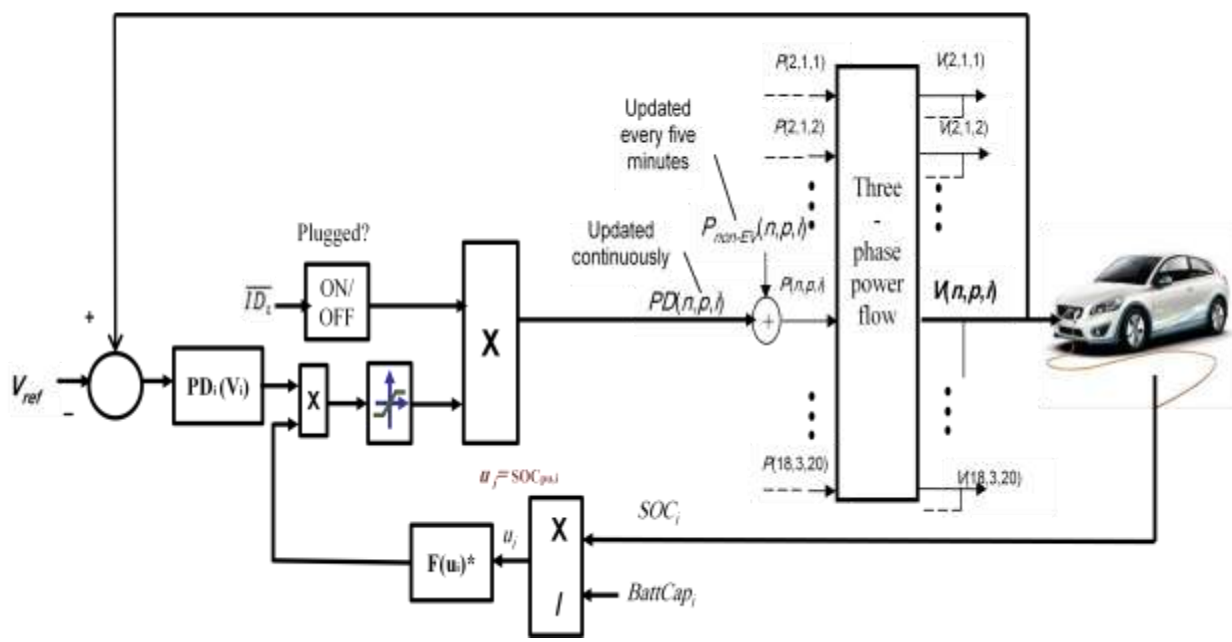

Figure 3- 3 Simulation setup

3.2 Voltage Based Feedback Controller

An electric vehicle charger converts the AC current from the grid into a constant DC current to charge the batteries. From the grid, the EV, therefore, is often seen as a constant current source [61]. When connected to the grid through an SAE J1772 charging station, a pilot signal $\overline{ID_i}$ is supplied to the EV from the station to initiate or stop the charging process and tells what the maximum AC current that can be drawn from that connection point is. The EV charges at that current unless the battery management system reduces the maximum current draw to improve battery life near the end of the charging cycle, or if the EV charger cannot handle that high current level. The proposed voltage-based controller adjusts this EV charging current, and therefore the charging load, based on the AC voltage observed at the point of connection.

The direct objective of the EV battery charging control is to maintain the distribution system nodal voltages $V(n,p,i)$ within acceptable limits. This will ensure that the feeder losses are reduced and overloads are avoided [27]. At a given distribution transformer, the load is the composition of controllable and non-controllable loads. Since the voltage profile of the system is a function of its loading levels, the voltage profile can be significantly enhanced by controlling the load. In this work, the only controllable loads are the EVs.

In the proposed control structure, the feedback signal that is used as an input for the controller is the voltage at the point of charging (POC). The controller output is the regulated charging rate, or the charger power draw (*PDi*). Since unidirectional power flow is assumed, the charging power minimum (minimum charging current * nodal voltage) limit is zero and its maximum limit is taken from the EV charger specifications or the maximum rating of the charging station, whichever is lower. For each EV, based on the POC voltage and the EV battery SOC (State of Charge), the controller decides on the regulated charging power.

Notice that there is one controller per EV. In order for the charging current, *IDi*, to be nonzero for a plugged-in EV whose SOC is not yet full, the voltage at the POC must be within permissible limits.

The left hand side of Figure 3-3 shows a block diagram for the voltage feedback controller. In its simplest form, the proposed controller represents a nonlinear proportional relationship between the EV charging rate $ID_i = (PD(n,p,i)/V_i)$ and the voltage at the POC. The output of the controller is continuous. Hence, the regulated charging rate, ID_i, can take on any value between 0 and $\overline{ID_i}$ over a wide range of nodal voltage levels. As long as the $SOC_i < BattCap_i$ (maximum battery capacity) and $V_i > V_{ref,i}$, the regulated current charging rate, ID_i, can be stated as

$$ID_i = ID_{max} - (ID_{max} - ID_{min})\, e^{-(\alpha(Vi - Vref,i))} \tag{3.1}$$

Where ID_{max} and ID_{min} are the maximum and minimum values of current draw, $V_{ref,i}$ is the reference voltage level for the ith EV in pu, $V_i = V_{(n,p,i)}$ is the actual real-time voltage in pu at the POC, and α is a constant to increase or decrease the charging rate.

Because the system loading is measured in power, not current, it is helpful to refer to the EV power draw, PD_i, which is merely the current draw ID_i, multiplied by the node voltage. Therefore, for the rest of this work, only PD_i will be referenced even though it is ID_i that is actually directly modulated. Thus, the regulated power charging rate, PD_i, can be stated as

$$PD_i(V_i) = \begin{cases} PD_{max} - (PD_{max} - PD_{min})\mathrm{e}^{-\left(\alpha(V_i - V_{ref,i})\right)} & if\ V_i > V_{ref,i} \\ 0 & if\ V_i \le V_{ref,i} \end{cases} \quad (3.2)$$

Where PD_{max} and PD_{min} are, respectively, the maximum and minimum power draws, i.e. charging rates.

From (3.2), it can be seen that if V_i is close to $V_{ref,i}$, the charging rate is close to PD_{min}. However, as V_i increases, PD_i will increase. This ensures that the charging rate increases whenever there is room in the grid for higher power draw.

A very important aspect of an EV charging strategy is "fairness". That is, the contribution of each EV to mitigate voltage violations should be decided upon in a manner that does not consistently charge an EV significantly slower or faster than another EV based on their locations in the network. This fairness can be thought of in two directions horizontal fairness and vertical fairness. Horizontal fairness corresponds to the fact that EVs charging at about the same voltage levels should be charging at similar charging rates PD_i. Since V_i for all these EVs are approximately the same, horizontal fairness can be achieved by simply setting $V_{ref,i}$ of these EVs to be identical. Vertical fairness is related to the level of contribution of EVs connected to POCs at different voltage levels (EVs at upstream node 2 and downstream node 6). It is desirable that all EVs connected to the same feeder to have almost equal charging opportunities. That is, it won't be appropriate or acceptable that EVs connected to downstream, i.e. lower voltage, POCs suffer from much lower regulated charging rates than those connected to upstream, i.e. higher voltage, POCs. Vertical fairness can be improved by using a charging rate function that is not excessively sensitive to the voltage level. Otherwise, EVs connected upstream will have an unfair advantage due to their higher voltage level over EVs connected downstream. It is only when the voltage is considerably high that the charging rate should increase.

Note that the voltage set points, $V_{ref,i}$, will be kept constant at 0.955 p.u for all EVs at all POCs. This voltage reference will be kept constant in all cases regardless of seasonal variations. If the voltage is below this set point at a given POC, the charging rates for all EVs connected to that POC should be set to zero. However, because of the way the charging rate function is set up, PD_i in (3.2) has a discontinuity at $V_i=V_{ref,i}$. In order to ensure smooth transition of the power draw from PD_{min} to zero, a ramp-rate limiter is applied.

3.2.1 Charging as a Function of State of Charge

An additional property that is added to the control scheme is the dependence of the charging rate on the EV battery SOC. This is included by multiplying $PD_i(V_i)$ in (3.2) by $F(ui)^* =$ exp(1–$SOC_{pu,i}$), where exp(.) stands for the exponential function and $SOC_{pu,i}$ = $SOC_i/BattCap_i$. This term will bias the effective charging rates more towards the least charged EVs and less towards the most charged EVs. Because $SOC_{pu,i}$ changes over a wide range (between 0 and 100%) and because Vi changes over a limited range in normal operational conditions, the resulting charging rate is more sensitive to changes in $SOC_{pu,i}$ than to changes in Vi. This is a desirable feature.

3.2.2 Preferred End-of-Charge Time (ECT)

The control scheme is further modified in order to include any possible preference of the ECT for the EV owner. This is done by limiting the EV power draw to a value that is dependent on the remaining uncharged battery capacity. Thus, the minimum power draw for each EV is defined as the average value required over the remaining charging interval. That is, for an EV with a current state of charge of SOC(t) and a total battery capacity of $BattCap_i$, the power draw is modified to

$$PD_i(V_i, SOC_{pu,i}) = \begin{cases} PD_i^* & if\ V_i > V_{ref,i} \\ 0 & if\ V_i \le V_{ref,i} \end{cases} \tag{3.3}$$

Where

$$PD_i^* = \max\begin{Bmatrix} PD_i(V_i)\mathrm{e}^{(1-\mathrm{SOC}pu,i(t))}, \\ (BattCap_i - SOC(t))/(d-t) \end{Bmatrix} \tag{3.4}$$

Where *d* is the preferred total charge time (in hours), set by the EV owner. Note that this additional term cannot guarantee that the EV will charge fully before the ECT. This is because the PD_i^* term in (3.3) applies only when the POC voltage is higher than $V_{ref,i}$. Otherwise, PD_i will be set to zero. Therefore, in extreme conditions, some of the EV owners with preferred ECT might not by granted their preference.

Figure 3-4 show a flow chart of the charging process where the EV will start charging only if it is plugged in and no voltage violation in the system.

3.3 Types of Charging Schemes

In order to test and show the effectiveness of the proposed control scheme, three types of charging schemes will be simulated. These schemes are described as follow:

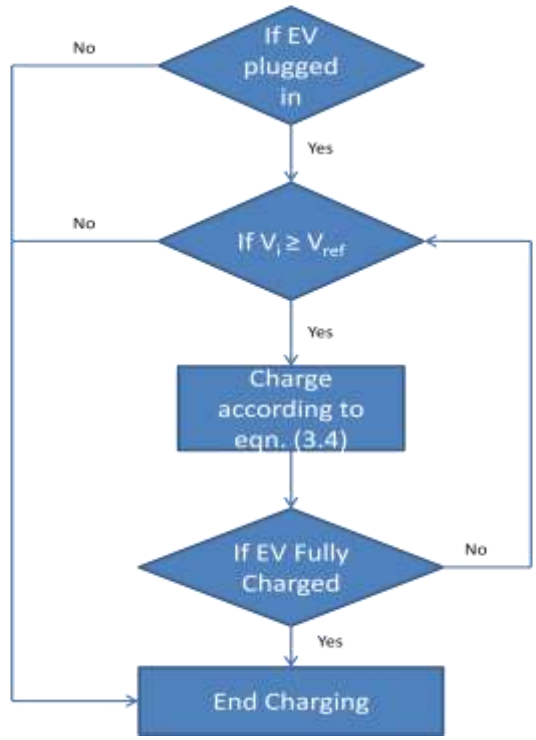

Figure 3- 4 Flow chart of charging process

3.3.1 Opportunistic Charging

Opportunistic charging can also be termed as dumb charging. In this type of charging there is no control over the charging rate of the EV battery. The EVs are assumed to be charged at the maximum allowable rate of their chargers as soon as they are plugged in.

3.3.2 Charging Using Constant Proportional Control and Flat Voltage References

In this type of charging a fixed value of reference voltage is assigned to all the EV controllers. Constant proportional gain is used instead of equation 3.4. The proportional gain is the same for all EV controllers. The fundamental idea behind this charging scheme is to maintain the overall voltage profile of the system above the lower range and a value little bit higher than the lower range is set as a flat voltage reference. In this work the flat voltage reference will be 0.955 per unit which is 0.5% greater than lower permissible voltage of 0.95 per unit.

3.3.3 Charging Using Variable Controller Gains and Flat Voltage References

The idea behind this type of charging is to achieve fairness among EVs at various nodes of the distribution system. Fairness implies that EVs at upstream nodes with good voltage profile and EVs at downstream nodes with low voltage profile are charged at comparable rates and finished charging time is also as close as possible. To achieve fairness along with avoiding voltage violations, two aspects have been modified. The first aspect is to have variable controller gains. The method described in section 3.2 will be used here. The second aspect is to make the proportional EV control a function of battery SOC.

Variable gain based on the nodal voltage will be used instead of the constant gain used in the previous case. Also constant reference voltage points will be used. The main advantage of constant reference voltage points is that it removes the need to update the setting point due to seasonal variation or system reconfiguration which is common in power system. Also, the use of variable gain controller, based on local voltage measurement, provides flexibility of charging and increase the charging rate whenever there is a room for charging, e.g. cases of light loading in late night.

CHAPTER 4

SIMULATION RESULTS

To show the merits of the proposed EV charge control scheme, several simulations are conducted. It is assumed that 50% of the houses have EVs. Since the total number of the houses connected to each phase of the secondary transformer is 20 houses, this means each phase of the secondary transformer will have 10 EVs connected to it. The EVs at each phase are labeled in our system with numbers from one to ten. This means that we have EV1, EV2 up to EV10 connected to phase a. Also, it is the same for phase b and phase c.

The results for the three types of charging schemes discussed in the previous chapter will be shown. Results corresponding to nodes 2 and 6 are presented. The former is the most upstream primary load node with the highest voltage in the system, while the latter is the primary load node with the least voltage in the system due to its far distance from the substation and the large loads connected to it. Voltage results at the primary nodes are normalized by the Nominal System Voltage for a 12470Y/7200 rating and results at the POCs at the houses at the secondary of the transformer are normalized by the Nominal Utilization Voltage for a 240/120 rating. Since the Nominal Utilization Voltage is only 230/115 for a 240/120 rating, the POCs (at the secondary system) can have higher per unit voltage values than those of the nodes.

4.1 Opportunistic Charging

In opportunistic charging, the EVs are assumed to be charging at maximum charging rate as soon as they are plugged in. This case highlights the load response to a voltage change of the EV inverter/chargers. This response is approximately consistent with a constant current ac load for a Nissan LEAF. The charging stations themselves are assumed not to have any voltage response, which is the case for the vast majority of stations.

The results of opportunistic charging are shown in Figure 4-1 – Figure 4-6. Figure 4-5 and Figure 4-6 show a significant jump is observed in the total load within the first several hours of charging. In addition, a voltage dip, considerably below the permissible limit of 0.95 pu, due to the sudden and uncontrolled increase in loading is noticed at a number of primary nodes and secondary POCs and can be shown in Figure 4-2 – Figure 4-4. Figure 4-1 shows the voltage at the primary node 2. Figure 4-3 and Figure 4-4 just show results for number of EVs connected to phase a and phase c, but similar results can be noted for the other EVs.

Note that, in general, downstream primary nodes suffer from lower voltage profiles than upstream primary nodes. Therefore, two extreme cases are the POC (Point of Charging) with the shortest secondary wire length connected to primary node 2 (to be labeled as POC A), and the POC with the longest secondary wire length and least voltage connected to primary node 6 (to be labeled as POC B). POC A is expected to have a very high POC voltage, while POC B is expected to have a very low POC voltage. In the results that follow, more emphasis is given to these two extreme cases. Note that the bold curves in Figure 4-1 – Figure 4-6 correspond to these two POCs or to the primary nodes that each of them is connected to.

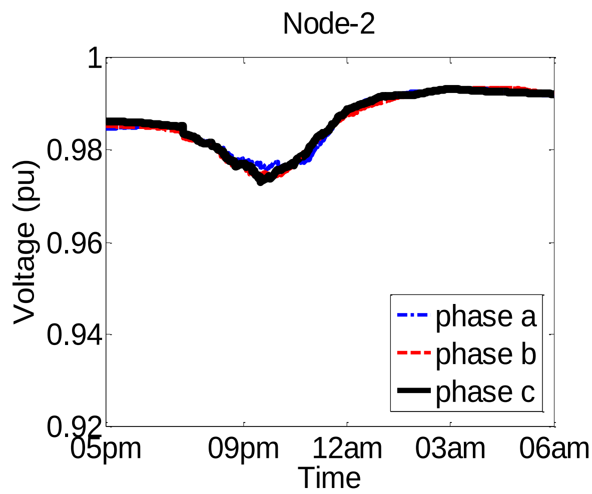

Figure 4- 1 Voltage profile at primary node 2 using opportunistic charging

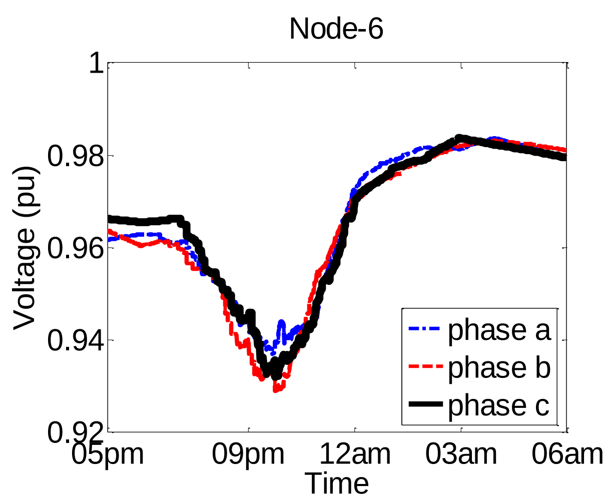

Figure 4- 2 Voltage profile at primary node 6 using opportunistic charging

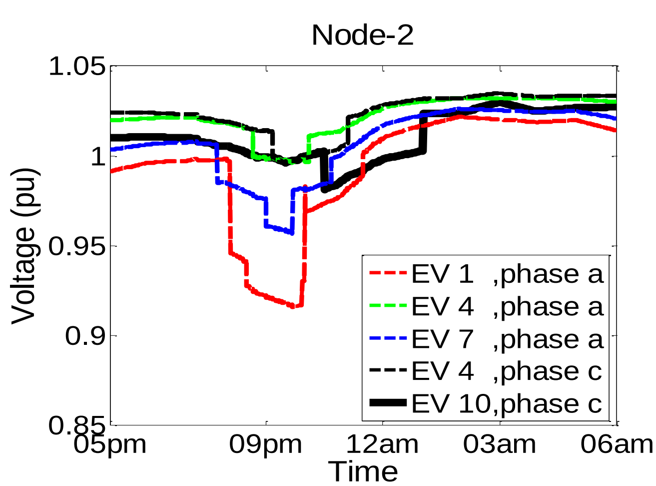

Figure 4- 3 Voltage profiles at several secondary POCs of node 2 including POCs A

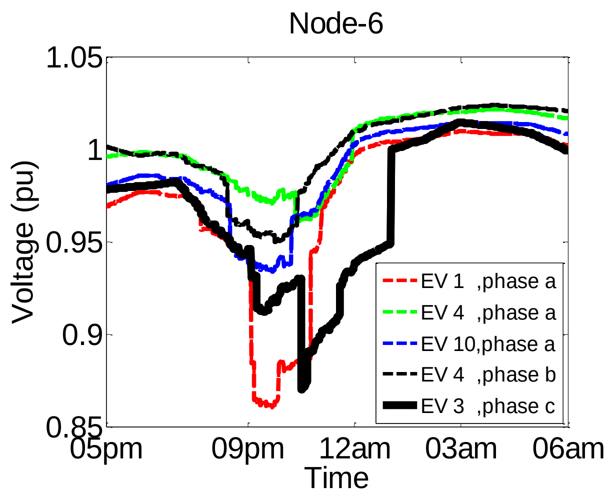

Figure 4- 4 Voltage profiles at several secondary POCs of node 6 including POCs B

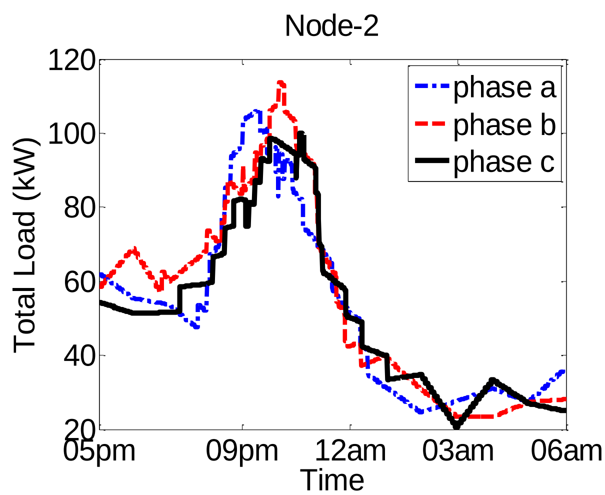

Figure 4- 5 Total loads at primary node 2 using opportunistic charging

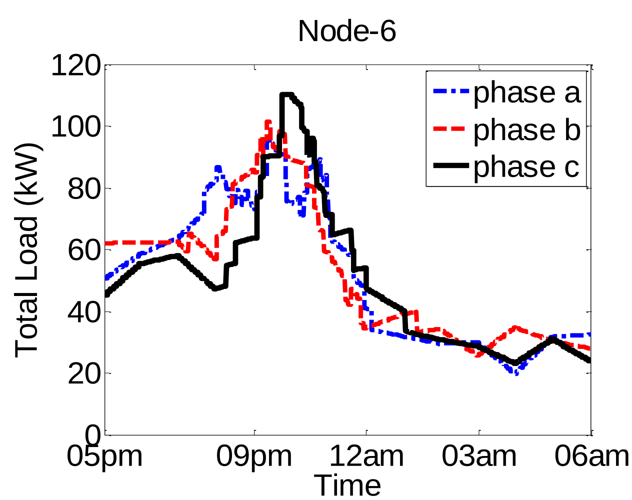

Figure 4- 6 Total loads at primary node 6 using opportunistic charging

4.2 Charging Using Constant Proportional Control and Flat Voltage References

In this case, the voltage set points of all EVs in the system are set at a flat voltage reference of 0.955 pu. This constant flat reference needs no updates with seasonal variation. After several trials, the constant proportional gain is set to 14 for all EVs. This value of the gain allows all the EVs to be fully charged before 6 a.m. SOC dependency is also used to ensure fairness. At this value of gain, all EVs are charged fully before the end of the charging period, i.e. before 6 a.m. Figure 4-7 – Figure 4-11 show the impact of using this basic proportional control scheme on the performances at nodes 2 and 6. The results clearly show the effectiveness of this simple, distributed control scheme on enhancing the voltage profiles, both at the primary node level and at the secondary POC level. Figure 4-9 and Figure 4-10 show that the voltage does not go below 0.95 and no voltage violation occurs. However, although the basic control scheme reduces voltage violations significantly, it does not greatly ensure fairness among the EVs.

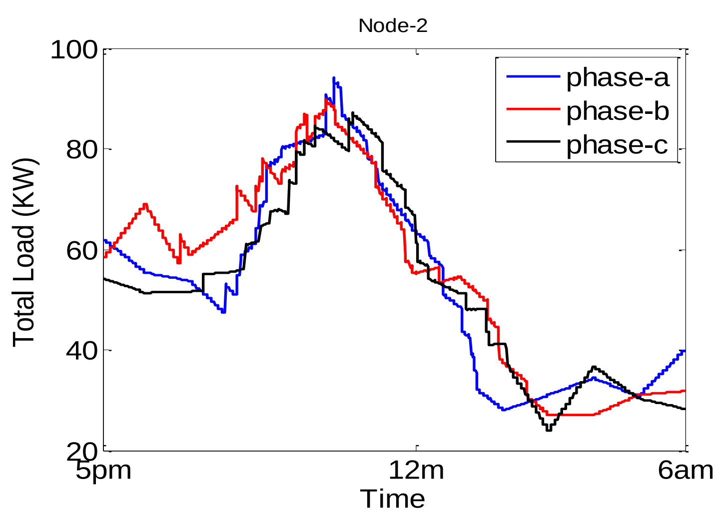

Figure 4- 7 Total loads at node 2 using basic proportional control with flat V_{ref}

This can be seen from comparing the EV SOC of POCs A and B in Figure 4-11. This should be expected since the same voltage reference value of 0.955 pu is used at all POCs and a constant gain was used. Because POC B is worse off than POC A in terms of secondary wire lengths and primary nodal voltage, its voltage level is always lower than that of POC A. Therefore, POC B's EV will always be at disadvantage and will be charged at much lower rates.

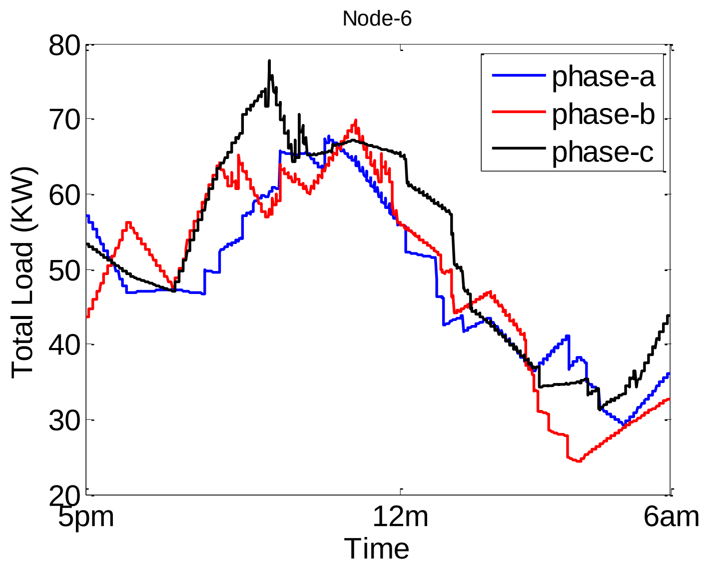

Figure 4- 8 Total loads at node 6 using basic proportional control with flat V_{ref}

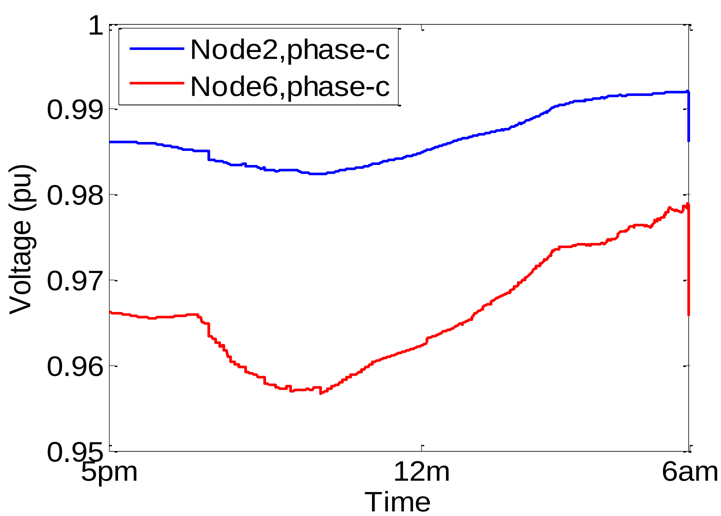

Figure 4- 9 Voltage profiles at nodes 2 and 6 using basic proportional control with flat V_{ref}

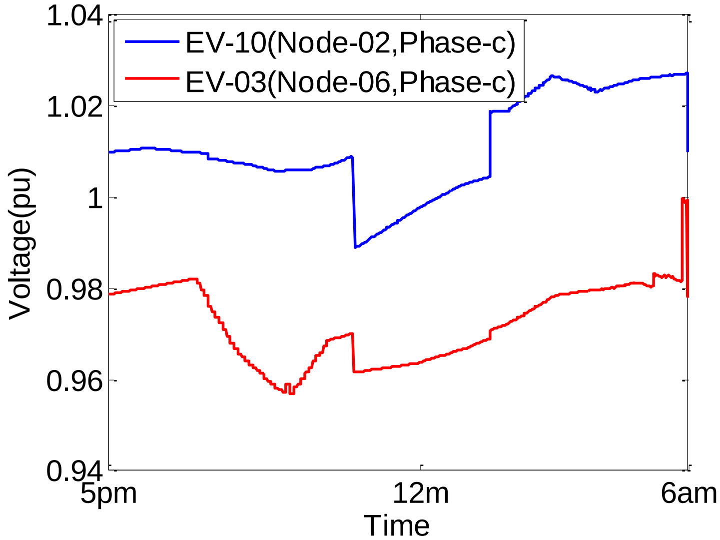

Figure 4- 10 Voltage profiles for POCs A and B using basic proportional control with flat V_{ref}

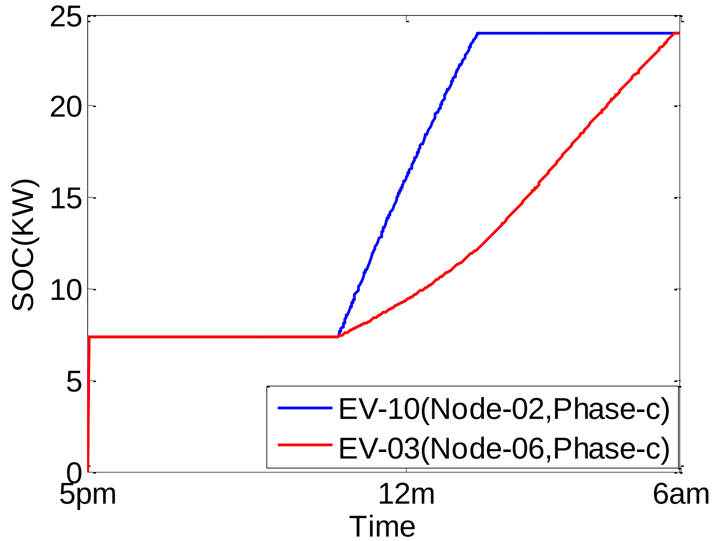

Figure 4- 11 SOC for POCs A's & B's EVs using basic proportional control with flat V_{ref}

4.3 Charging Using Variable Controller Gains and Flat Voltage References

In order to improve the charging fairness, variable gain controller is used and the voltage set point is flat voltage reference of 0.955. The effective gain of the *PD* in this case will not be constant, but will vary continuously according to equation (3.2). The values of PD_{max} and PD_{min} are chosen to be 0.7 and 0.3, respectively. These values were obtained by trial and error. An important advantage of using constant set points and variable gains is that it will still provide fairness when capacitors and other voltage control devices are in use in the system and it needs no adjustment of the set points for seasonal load variations once it is well adjusted at the beginning.

Fairness is improved even further by making the variable gain a function of the battery SOC according to equation (3.4). The effective gain exponentially decreases as $SOC_{pu,i}$ increases which ensures more fairness among different EVs with different SOCs and it increases the battery life time since the charging rate greatly decreases near the end due to the exponential dependency.

Figure 4-12 – Figure 4-18 show the nodal loads, nodal voltage profiles, POC A's and B's voltage profiles and their SOCs, total distribution system load and the average charging rate at node 2 and node 6 due to the use of a more fair SOC-dependent variable control scheme. Comparing the SOC resulting from using the variable gain controller with the SOC resulting from using basic proportional control clearly shows significant improvement in the level of fairness by reducing the differences among the EVs in terms of how fast each of them fully charges. The figures show no voltage violations even at the most downstream POC. In addition, although node 2 (upstream node) has a higher voltage than node 6 (downstream node), the proposed controller greatly reduces the gap in charging time between the EVs connected to each of the nodes. This is because SOC-dependency which makes the effective charging rate decrease gradually as SOC_{pu} gets higher.

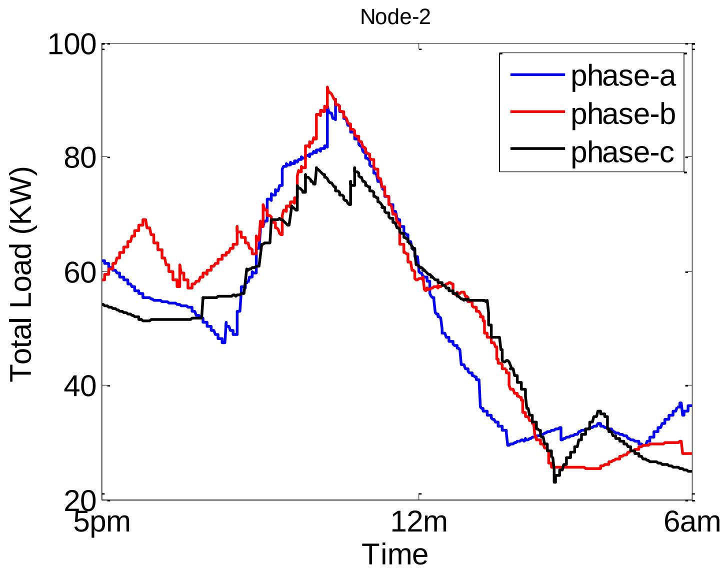

Figure 4- 12 Total load at node 2 using fair, SOC-dependent control

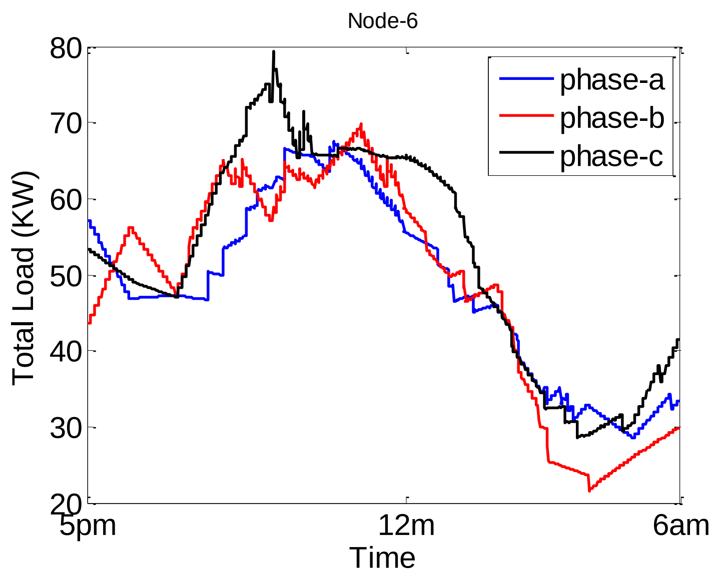

Figure 4- 13 Total load at node 6 using fair, SOC-dependent control

While the focal point of this research is the distribution system, these load profiles in Figure 4-17 indicate that this new scheme also benefits the bulk power system by shaving the evening peak load through delaying some of the EV charging load to night and early morning hours.

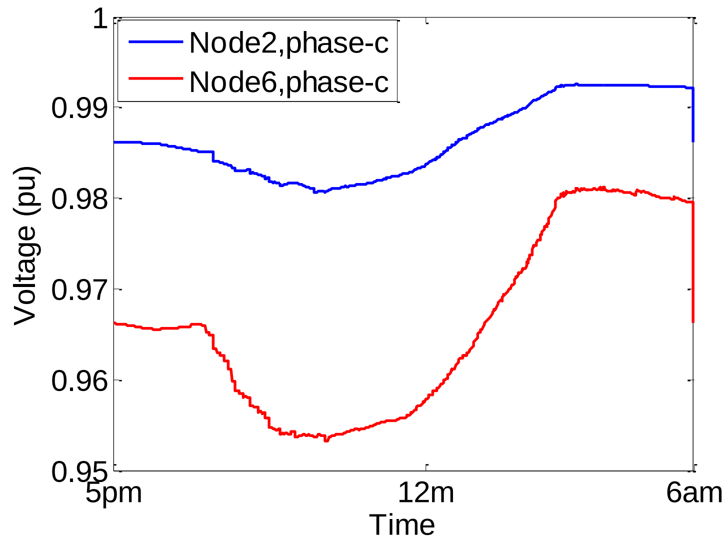

Figure 4- 14 Voltage profiles at nodes 2c and 6c using fair, SOC-dependent variable control

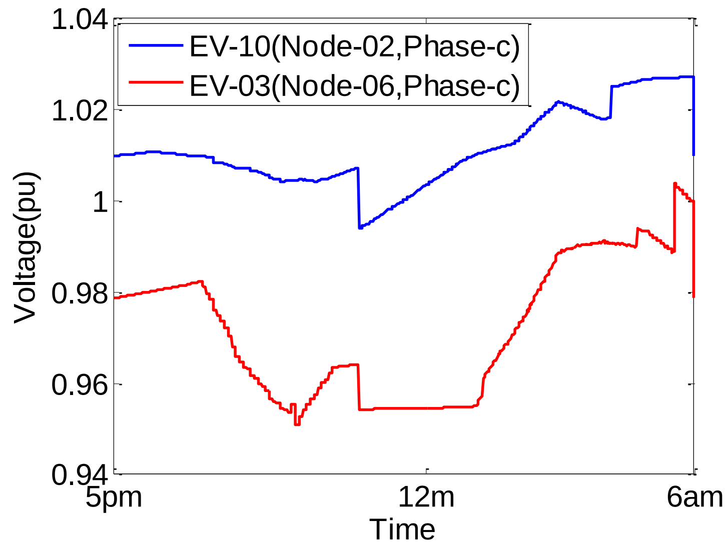

Figure 4- 15 Voltage profiles for POCs A's and B's EVs using fair, SOC-dependent variable control

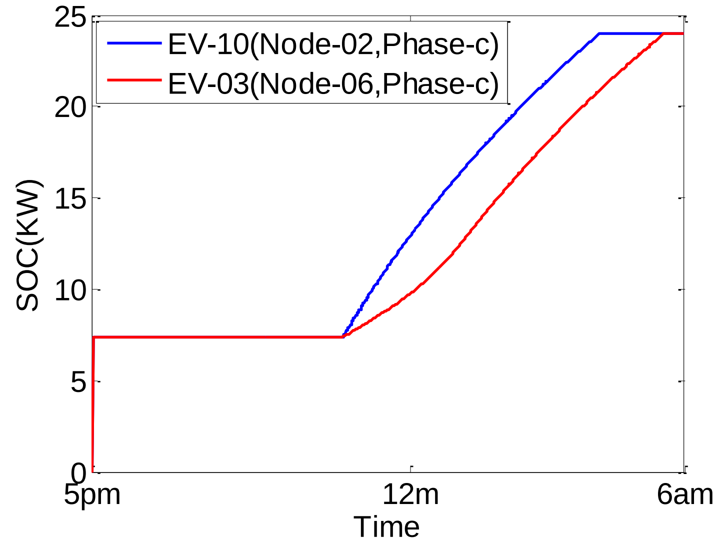

Figure 4- 16 SOC for POCs A's & B's EVs using fair, SOC-dependent variable control

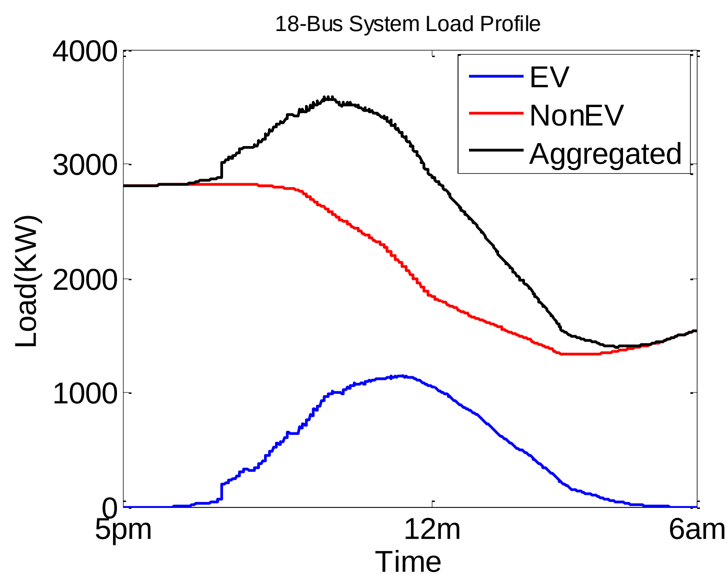

Figure 4- 17 EV, Non EV and Total loads for the distribution system using fair, SOC-dependent variable control

As can be seen that from Figure 4-12 – Figure 4-18, although the node 2 (upstream node) has a higher voltage than node 6 (downstream node), the variable controller greatly reduces the gap in charging time between both.

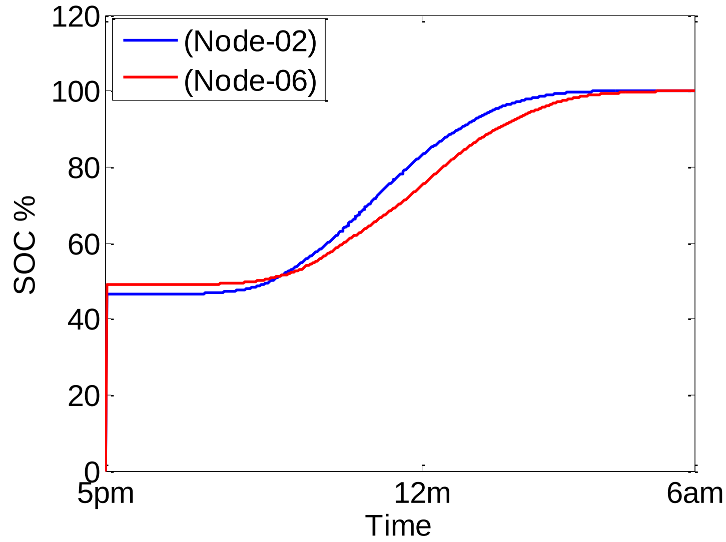

Figure 4- 18 Average charging rate at node 2 and node 6 using fair, SOC-dependent variable control

From Figure 4-17, it can be seen that the variable controller charges all the EVs as soon as possible, as long as there is no voltage violation. However, the higher the gain, the faster the rise in voltage is toward the end of intense charging period. This is because a higher gain makes the EV charge in a narrower time window, which results in more abrupt transition from the period of intense charging to the period of no charging. Therefore, one of the advantages of SOC-dependency is that it tends to slow down this abrupt transition. This is because as battery SOCs get higher, the effective controller gains are lowered and the actual power drawn by each EV gets reduced. This transition issue is further mitigated, to some extent, by the natural randomness of the plug-in times.

Although multiple tests are required to ensure proper controller tuning, one important advantage of this control scheme is that it consists of only two parameters to be tuned with no need to change the voltage set point even with seasonal variations. This simplifies the tuning process.

Table 4-1 summarizes the comparison in performance among the two voltage feedback control schemes. It shows the effectiveness of SOC-dependent variable controller in closing the gap between POCs A's and B's times to full charge. While only the results corresponding to POC A and POC B are shown, the EVs at the other POCs follow a similar trend.

Table 4- 1 Comparison in Terms of Time to Full Charge in Hours

Constant Vs. Variable Gain Schemes

Gain	Node-02	Node-06	Difference
	POC A	POC B	
Constant gain	3.05	7.375	4.325
Adaptive gain	5.6416	7.0583	1.4167

CHAPTER 5

CONTROL SCHEME PERFORMANCE ANALYSIS

In this chapter, the performance of the proposed variable, SOC-dependent EV charge control scheme is further studied. All the subsequent tests are carried out for the case of fair and SOC-dependent charging with PD_{max} and PD_{min} chosen to be 0.7 and 0.3.

5.1 Electric Vehicles Penetration Level Test

The robustness of the proposed control scheme with respect to varying levels of EV penetrations is first assessed. Table 5-1 shows a comparison in terms of the time needed to fully charge the EVs at nodes 2 and 6. The average and latest charging times at phase c of the two nodes as well as the charging times for EVs connected to POCs A and B are shown for EV penetration levels of 40%, 50% (base case), and 60%. The results demonstrate reasonable tolerance of this control scheme to different levels of EV penetrations up to 50%. If the penetration depth is increased above this value, POC B will not be able to charge fully before 6 am which means that there is no enough room in this system under study for penetration depths above 50%. This indicates that the system needs to be upgraded. This matches the real life case where each system has a maximum limit of loads, after which it should be upgraded.

Table 5- 1 Comparison in terms of time to full charge (in Hours) – SOC-dependent scheme at Different EV Penetration Levels

Penetration Level (%)	Node-02			Node-06		
	POC A	Mean Phase c	Latest	POC B	Mean Phase c	Latest
40	5.175	4.429	5.192	5.66	4.488	5.825
50	5.642	5.344	5.708	7.13	5.966	7.492
60	5.95	5.928	6.1	-	-	-

5.2 System Reconfiguration Test

The robustness of the proposed control scheme with respect to probable system reconfiguration is also studied. This is carried out for simple reconfiguration events and severe node reconfiguration events. Simple reconfiguration is carried out by removing one representative peripheral node at a time from the distribution system to simulate switching that node onto an adjacent feeder during a reconfiguration event. For simple reconfiguration, Nodes 4 and 8 are removed one at a time. Figure 5-1 – Figure 5-4 show POC A's and B's voltage profiles and their SOCs, total distribution system load and the average charging rate at node 2 and node 6 in case of removing node 4. Removing node 8 shows almost the same performance, so only results for node 4 are shown.

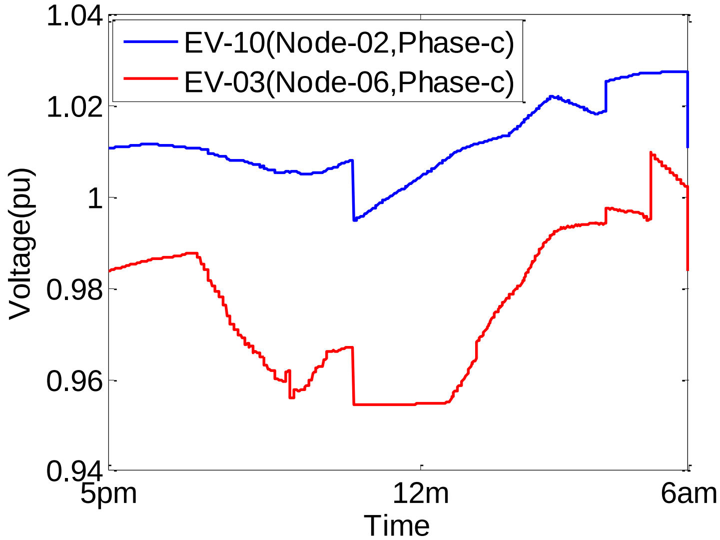

Figure 5- 1 Voltage profiles for POCs A's and B's EVs in case of dropping node 4

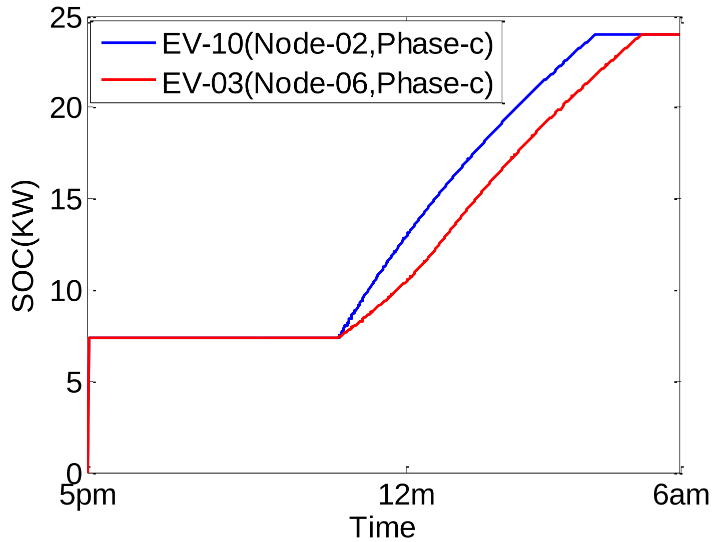

Figure 5- 2 SOC for POCs A's & B's EVs in case of dropping node 4

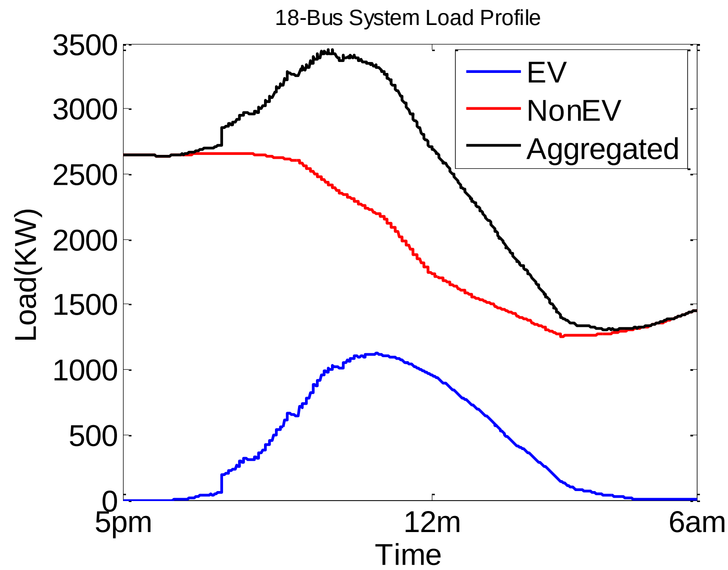

Figure 5- 3 EV, Non EV and Total loads for the distribution system in case of dropping node 4

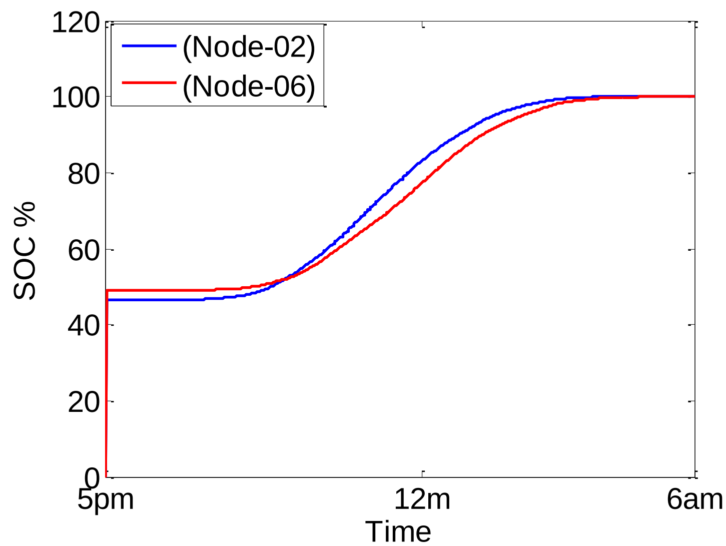

Figure 5- 4 Average charging rate at node 2 and node 6 in case of dropping node 4

Figure 5-2 shows an improvement in terms of how fast POC B charge. This improvement can be obvious by comparing Figure 4-16 to Figure 5-2. This improvement is expected since removing node 2 (i.e. feeding it from another feeder after reconfiguration) reduces the total load in the system. This reduction in load provides room for the vehicle to charge faster since there is more voltage margin.

For severe reconfiguration of the system, multiple nodes reconfiguration is carried out by removing nodes 10-18 simultaneously (which are almost half of the system).

Figure 5-5 – Figure 5-8 show POC A's and B's voltage profiles and their SOCs, total distribution system load and the average charging rate at node 2 and node 6 in case of severe reconfiguration case. The results show clearly the effect of removing half of the system on the electric vehicles charging rate.

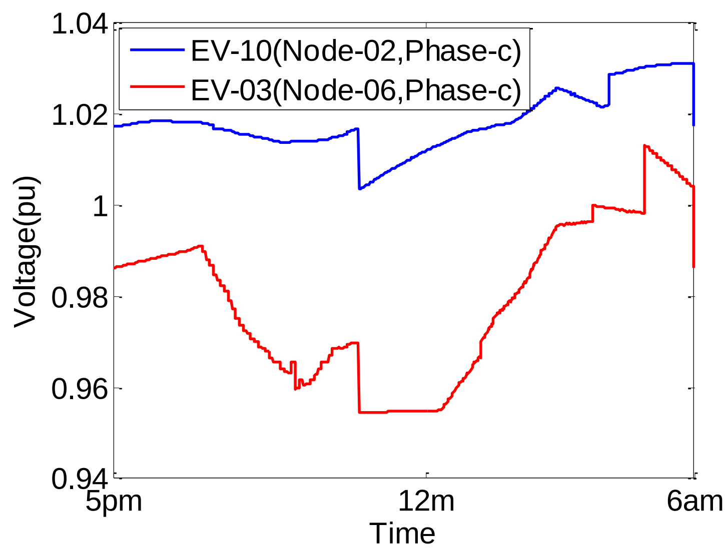

Figure 5- 5 Voltage profiles for POCs A's and B's EVs in case of severe reconfiguration

Figure 5-7 shows the reduction in the system loading due to removing nodes 10-18. This reduction in load results in fast charging of all the electric vehicles connected to the system. This is can be seen in Figure 5-8 which shows the average charging rate at node 2 and node 6 where the difference in charging rate between the upstream and downstream nodes has greatly reduced. This can be obvious if we compared Figure 5-8 with base case in Figure 4-18.

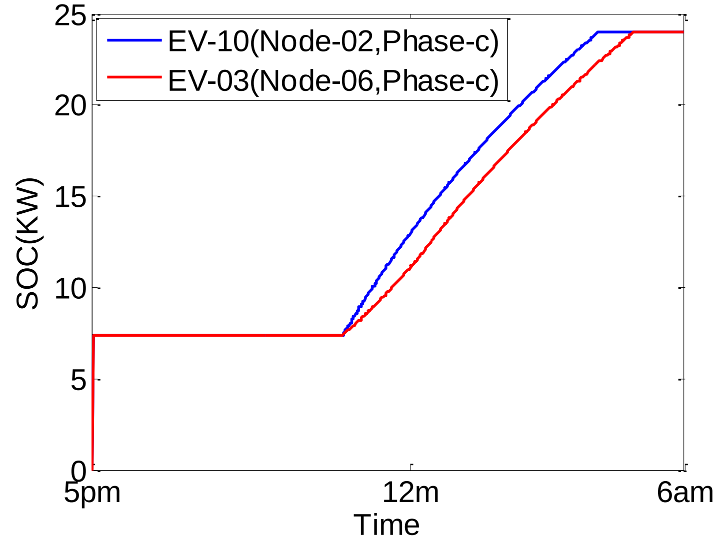

Figure 5- 6 SOC for POCs A's & B's EVs in case of severe reconfiguration

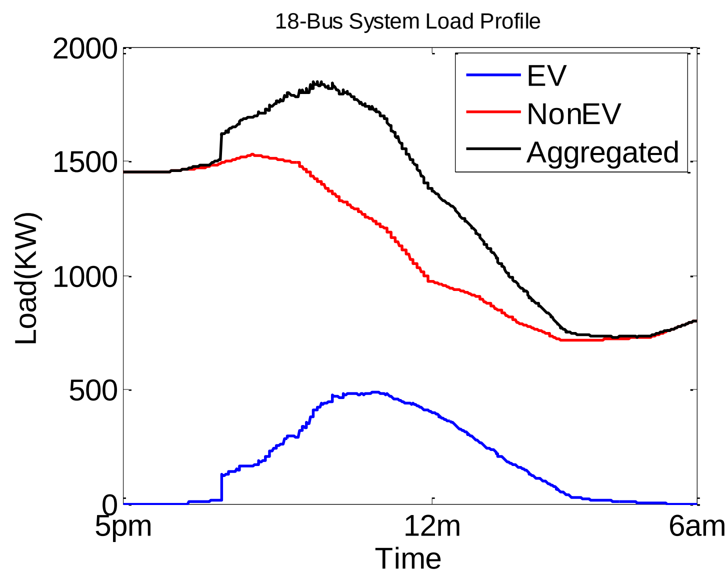

Figure 5- 7 EV, Non EV and Total loads for the distribution system in case of severe configuration

Table 5-2 shows the corresponding charging times for simple and severe reconfiguration events. These results confirm the robustness of the proposed scheme to moderate and severe system reconfigurations.

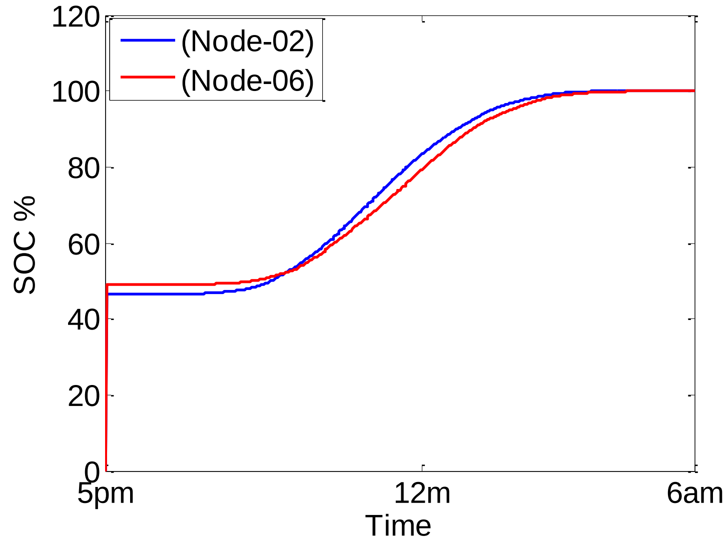

Figure 5- 8 Average charging rate at node 2 and node 6 in case of severe reconfiguration

Table 5- 2 Comparison in terms of time to full charge (in Hours) – SOC-dependent scheme after Disconnecting Nodes and case of light loading

Case	Node-02			Node-06		
	POC A	Mean Phase c	Latest	POC B	Mean Phase c	Latest
Node # 04 removed	5.642	5.338	5.7	6.66	5.69	6.917
Node # 08 removed	5.642	5.338	5.7	6.8	5.832	7.45
Nodes # 10-18 removed	5.6	5.291	5.65	6.38	5.51	6.475
Light loading	5.6	5.296	5.65	6.1	5.283	6.1

5.3 Different Loading Test

System performance during light load condition is also studied. This is done by reducing the non EV loads. Also the results in terms of full time to charge are included in Table 5-2. Figure 5-9 – Figure 5-12 show POC A's and B's voltage profiles and their SOCs, total distribution system load and the average charging rate at node 2 and node 6 in case of light loading. It can be seen that, since there is a room for charging, the EV at POC B charges faster. Also, it can be seen from Figure 5-12 that the average charging rate at upstream and downstream nodes is almost the same which means almost complete fairness in the system in case of light loading. This is due to large reduction in non EV loads which results in fast charging of all the electric vehicles connected in the system.

Unlike the case of severe reconfiguration in section 5.2, only non EV loads (non controllable loads) are reduced in case of light loading. In case of severe reconfiguration, both the EV as well as the non EV loads are reduced since they both feed from another feeder, however the in both cases, we reach almost the same effect and result.

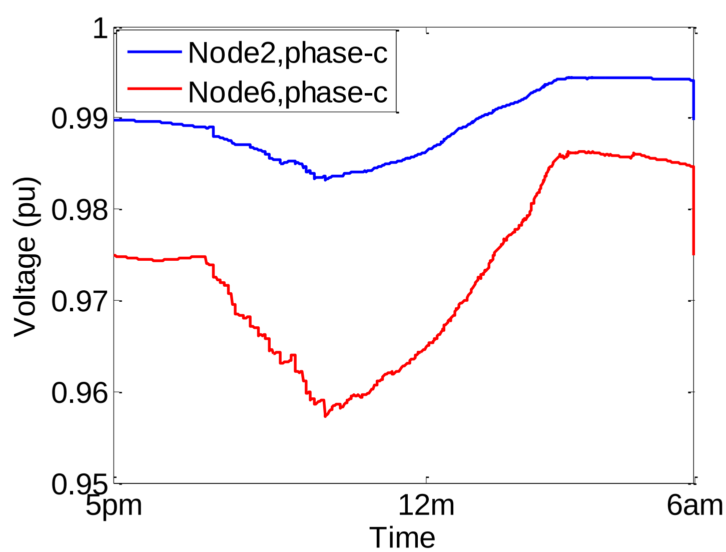

Figure 5- 9 Voltage profiles for POCs A's and B's EVs in case of light loading

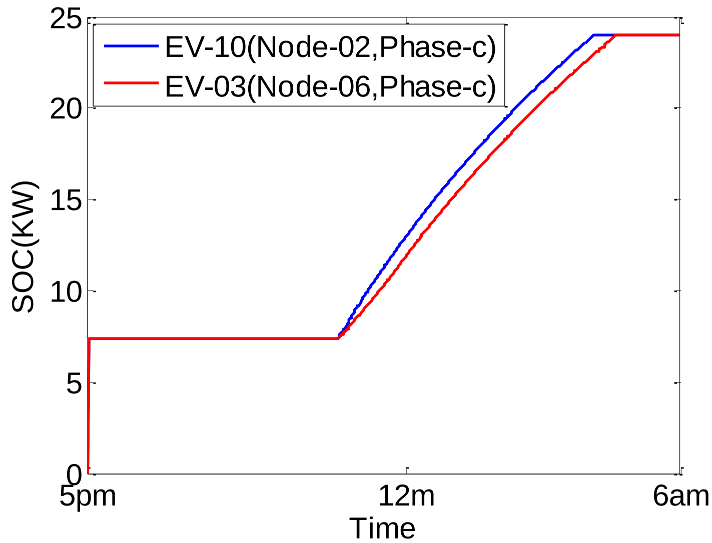

Figure 5- 10 SOC for POCs A's & B's EVs in case of light loading

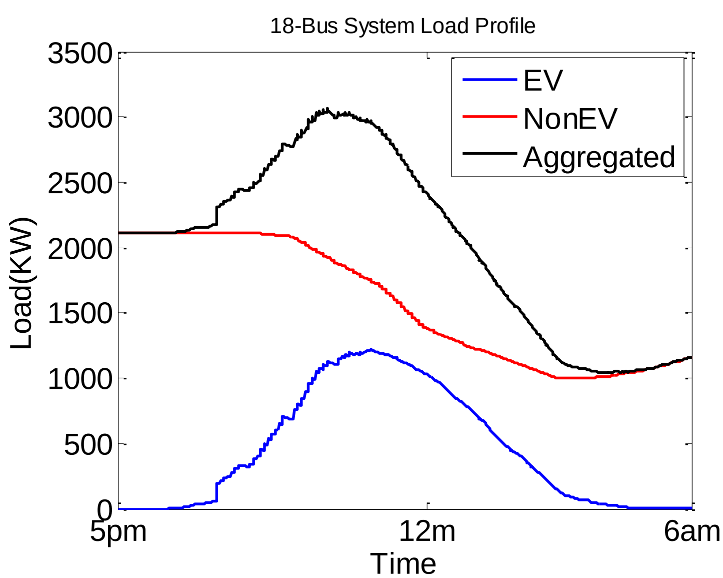

Figure 5- 11 EV, Non EV and Total loads for the distribution system in case of light loading

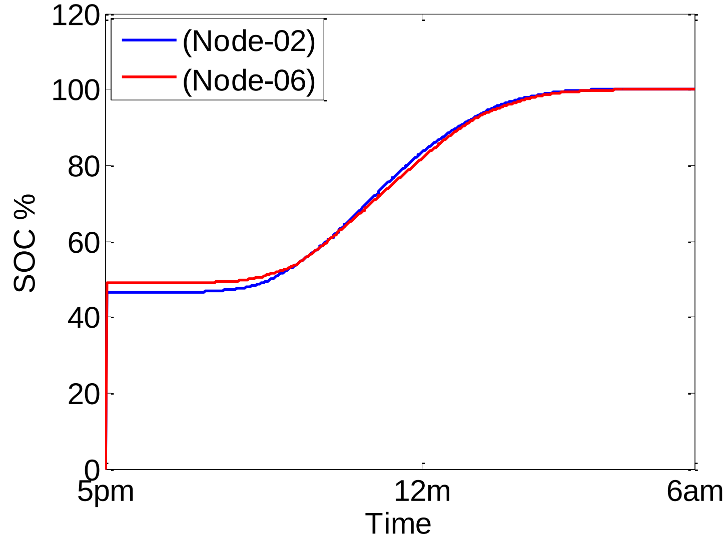

Figure 5- 12 Average charging rate at node 2 and node 6 in case of light loading

5.4 End of Charge Time Preference Test

An assessment of the performance of the charge controller due to an increase in the numbers of EV owners with preferred ECT is carried out as well. Figure 5-13 and Figure 5-14 show the test results for different percentages, 0%, 10% (base case), 30%, and 50% of owners simultaneously having preferred ECT. For each EV with a preferred ECT, a random integer number between 4 and 7 hours is assigned. The results show that this control scheme can accommodate a high percentage of EV owners with preferred ECT. Note that all EVs with preferred ECTs are charged fully before the specified ECTs. These tests show that once the parameters are tuned, changes in the system do not require retuning. This reduces the computational burden of implementing such a scheme.

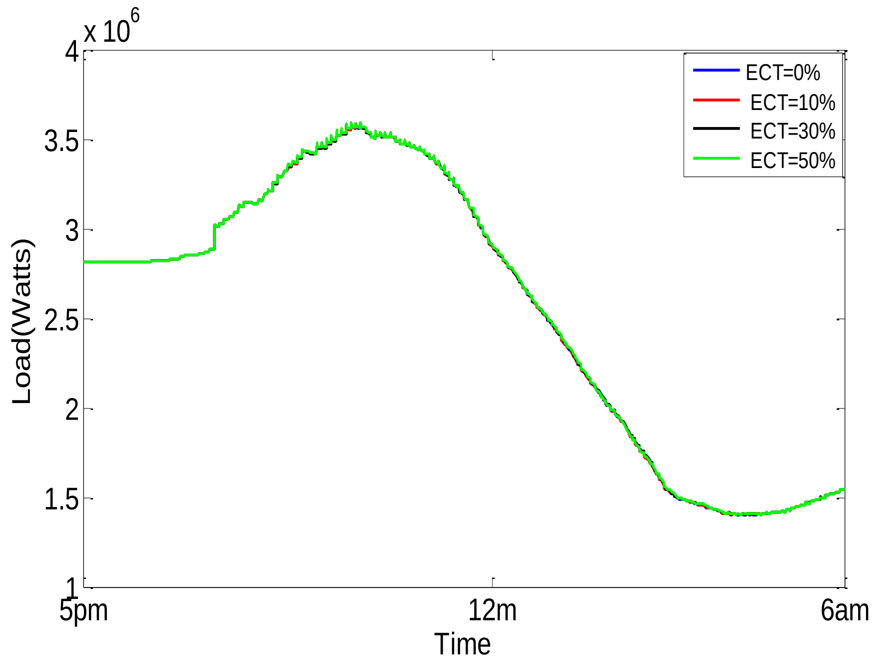

Figure 5- 13 Total load (EV + non-EV) for the distribution system at different percentages of EV owners with preferred ECT

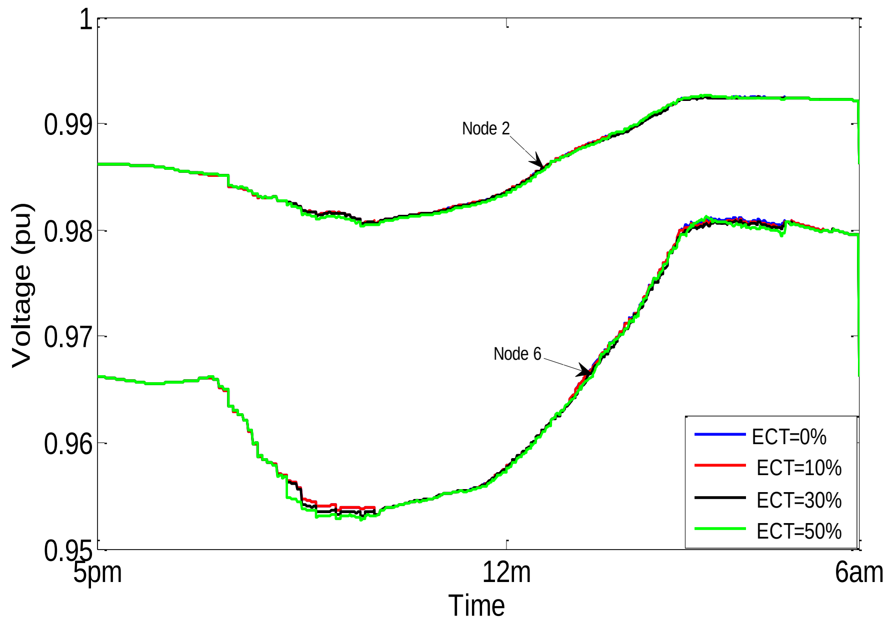

Figure 5- 14 Voltage profiles at nodes 2 and 6 at different percentages of EV owners with preferred ECT

CHAPTER 6

CONTROL SCHEME PERFORMANCE IN PRESENCE OF VOLTAGE CONTROL DEVICES

Voltage regulation is an important subject in electrical distribution engineering. It is the utility's responsibility to keep the customer voltage within specified tolerances. The performance of a distribution system and quality of the service provided are not only measured in terms of frequency of interruption but in the maintenance of satisfactory voltage levels at the customers' premises. A high steady-state voltage can reduce light bulb life and reduce the life of electronic devices. On the other hand, a low steady-state voltage leads to low illumination levels, slow heating of heating devices, motor starting problems, and overheating in motors. However, most equipment and appliances operate satisfactorily over some 'reasonable' range of voltages; hence, certain tolerances are allowable at the customer's end [62]. Thus, it is common practice among utilities to stay within preferred voltage levels and ranges of variations for satisfactory operation of apparatus as set by various standards such as IEEE standard 446. The basic function of voltage regulation in the distribution system operation is to keep the steady state voltage in the system stable within an acceptable range all the time. The desired voltages can be obtained by either directly controlling the voltage or by controlling the reactive power flow that in turn will affect the voltage drop. The equipment normally used for the voltage and reactive power control are on-load tap-changer (OLTC) transformers, switched shunt capacitors and steps voltage regulator. Such equipment are mostly operated based on an assumption that the power flows in one direction only and the voltage decreases along the feeder, from the substation to the remote end [63]. In this thesis, the control scheme performance will be tested in the presence of voltage regulator and shunt capacitor.

6.1 Coordination with Voltage Regulators

A voltage regulator is a tap-changing auto-transformer with the ability to continuously monitor its output voltage and automatically adjusts itself by changing taps until the desired voltage is obtained. A voltage regulator could be single phase or three phases with either 16 steps or 32 steps. The number of steps actually decide the per step voltage change; in case of 16 steps the per step voltage change is 0.00625 per unit while for 32 steps, it is 0.003125 per unit [16]. The assumptions made in this thesis are the same as in [16].

6.1.1 Simulation Results

The voltage regulator is connected at either node 2 or node 5 one at a time. Node 2 is chosen since it is the most upstream load node. Node 5 is instead of the downstream node 6 since it is more practical to connect the voltage regulator to that point in order to improve not only the voltage at that node, but also at nodes 6,7,8.

The settings of the voltage regulator are the following:

Voltage Set point

It is the voltage which the utility desires to maintain at the node at which the voltage regulator is connected. For this study it is selected as 0.99 per unit. We should note that this is different from the EV controller set point which is 0.955. Also, the controller set point is constant through the entire simulation.

Step Voltage

It is the amount of change in voltage caused by one step. This study is using 32 steps regulator, so the step voltage is 0.003125 per unit.

Bandwidth

It is the amount of variance allowed in voltage before regulator changes tap. This is selected as 0.003125 per unit.

Figure 6-1 – Figure 6-5 show POC A's and B's voltage profiles and their SOCs, taps for voltage regulator at node 2, total distribution system load and the average charging rate at node 2 and node 6 in case of voltage regulator (VR) connected to node 2.

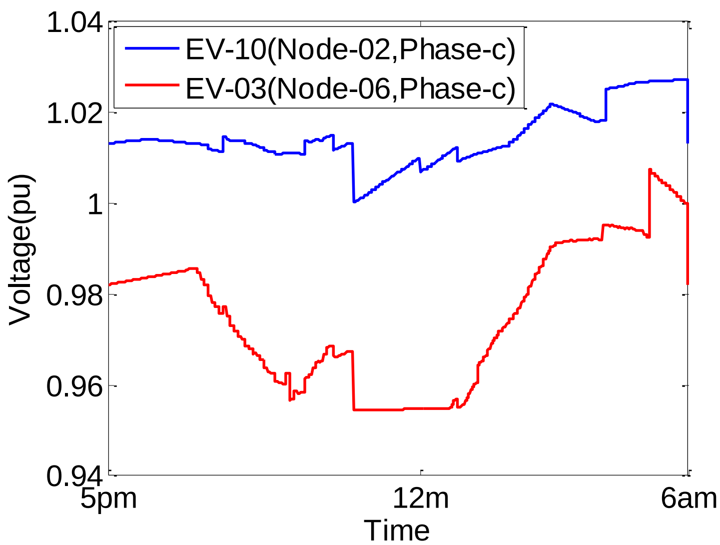

Figure 6- 1 Voltage profiles for POCs A's and B's EVs in case of VR at node 2

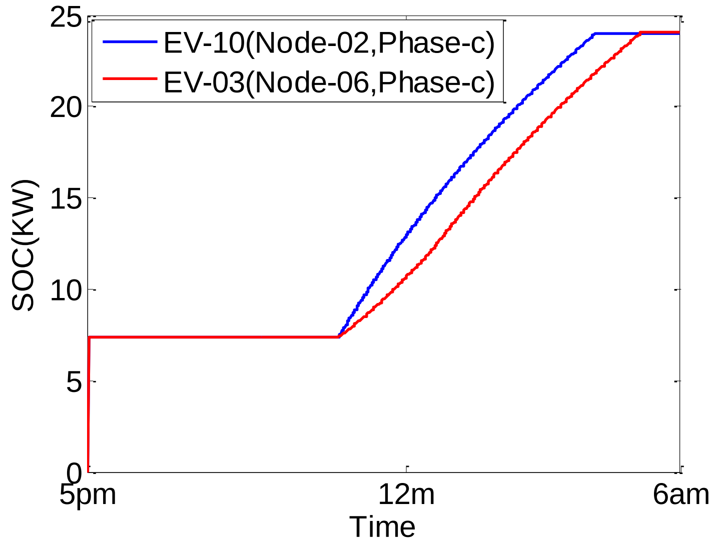

Figure 6- 2 SOC for POCs A's & B's EVs in case of VR at node 2

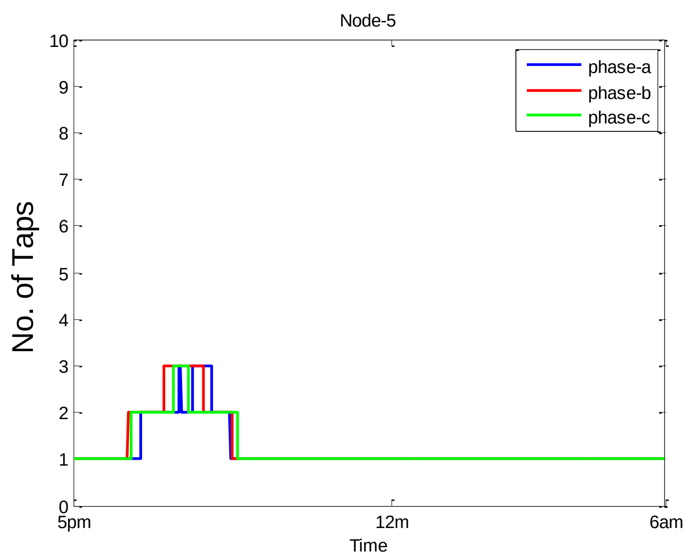

Figure 6- 3 Taps for voltage regulator at node 2

It can be seen from Figure 6-1 that the voltage of the upstream node 2, and hence the voltage of the houses connected to that node, is already close to or above the set point voltage 0.99. Therefore, there is no much change in the number of the taps of the voltage regulator. Figure 6-3 shows that the maximum change in number of taps is only 3.

However, the small effect of the voltage regulator can be seen by comparing the SOC for POCs A's & B's EVs in Figure 6-2 ,case of voltage regulator, and Figure 4-16 where there is no voltage control units. From the comparison, it is obvious that adding the voltage regulator increased the charging rate of the downstream node due to the slight increase in voltage.

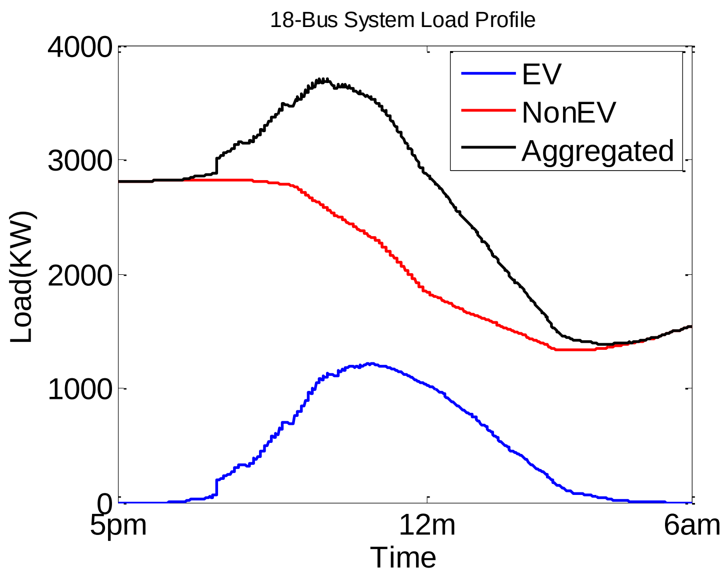

Figure 6- 4 EV, Non EV and Total loads for the distribution system in case of VR at node 2

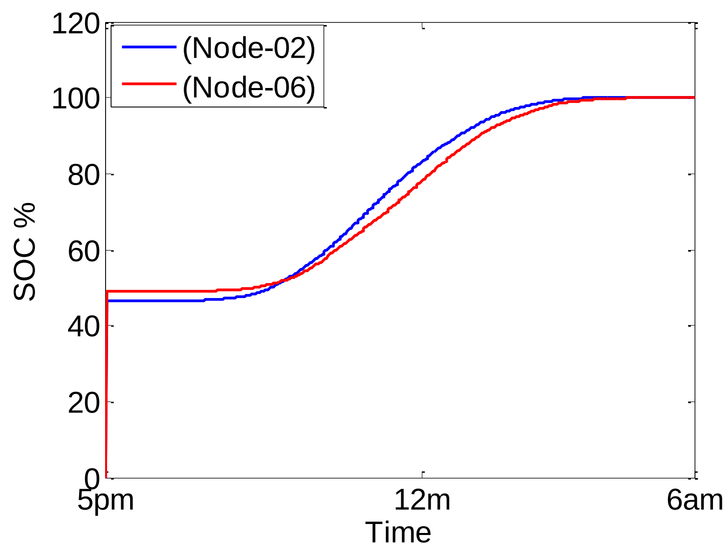

Figure 6- 5 Average charging rate at node 2 and node 6 in case of VR at node 2

Figure 6-6 – Figure 6-10 show POC A's and B's voltage profiles and their SOCs, taps for voltage regulator at node 5, total distribution system load and the average charging rate at node 2 and node 6 when voltage regulator (VR) connected to node 5.

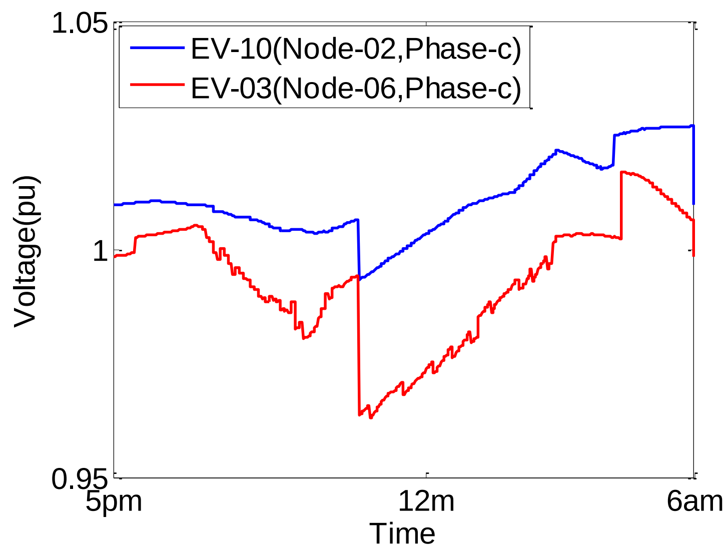

Figure 6- 6 Voltage profiles for POCs A's and B's EVs in case of VR at node 5

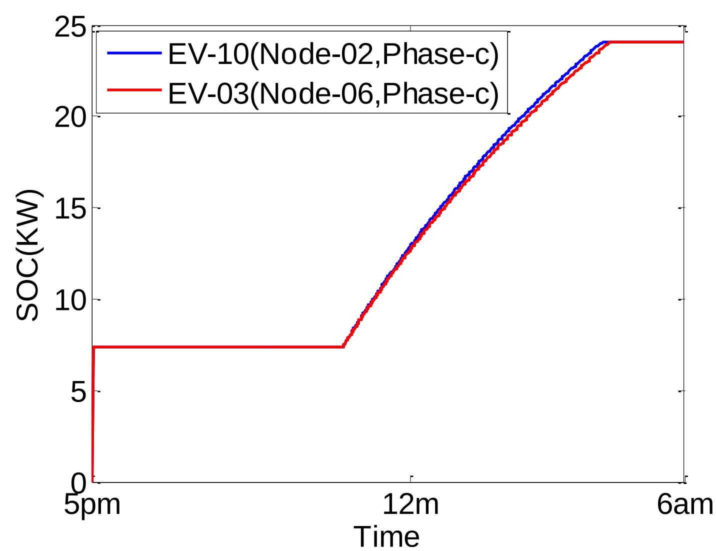

Figure 6- 7 SOC for POCs A's & B's EVs in case of VR at node 5

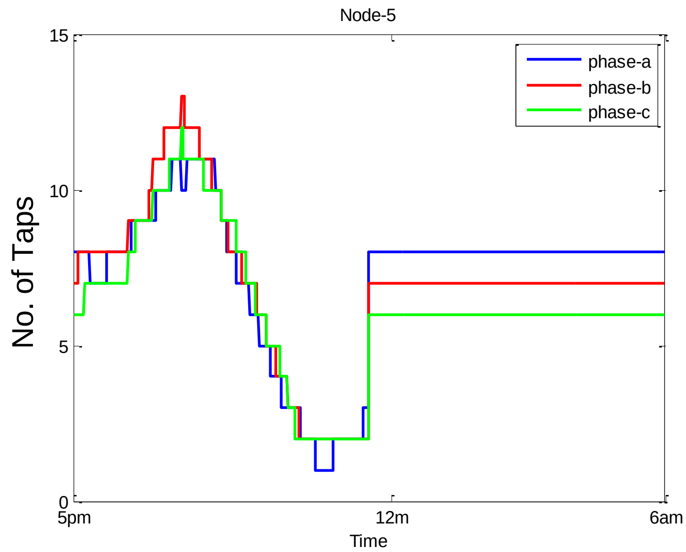

Figure 6- 8 Taps for voltage regulator at node 5

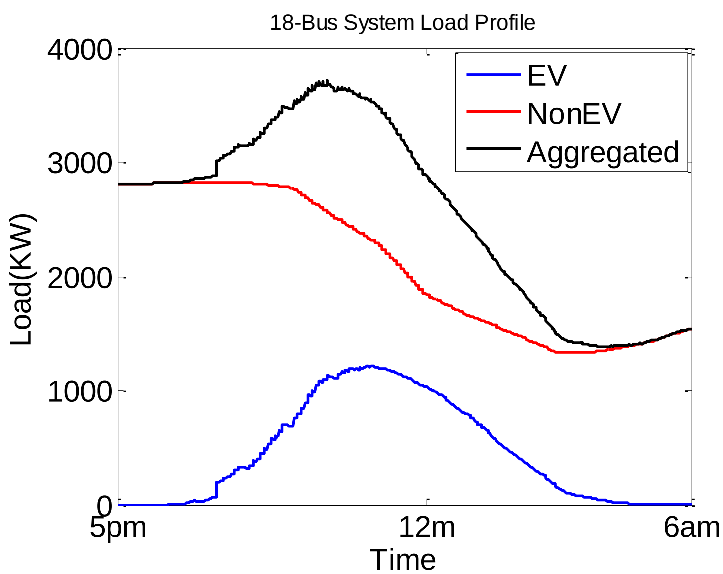

Figure 6- 9 EV, Non EV and Total loads for the distribution system in case of VR at node 5

By comparing the voltage profiles for POCs A's and B's EVs in case of VR at node 5 as shown in Figure 6-6 with the case where no voltage control units in Figure 4-15, it can be seen that the voltage has significantly increased by adding the voltage regulator at node 5.

This high increase in voltage leads to increasing the charging rate of the EVs connected to node 6 (the downstream node). Since both the upstream node 2 and the downstream node 6 have almost the same voltage, the EVs connected to them almost have the same charging rate. This can be shown in Figure 6-7 where SOC for POCs A's & B's EVs are almost the same. This also can be shown in Figure 6-10 where the average charging rate for all the electric vehicles connected to the upstream and downstream nodes is the same.

Since node 5 is a downstream node where its voltage is greatly lower than the set point voltage 0.99, the number of taps of the voltage regulator that are used at that node is large. Figure 6-8 shows the number of taps used at node 5. It is obvious that a large number of taps was used where the maximum number is 13 taps. It is worth mentioning that such large variation of taps does not practically happen. This means the controller will behave in a better way in practical situations since less variation will happen.

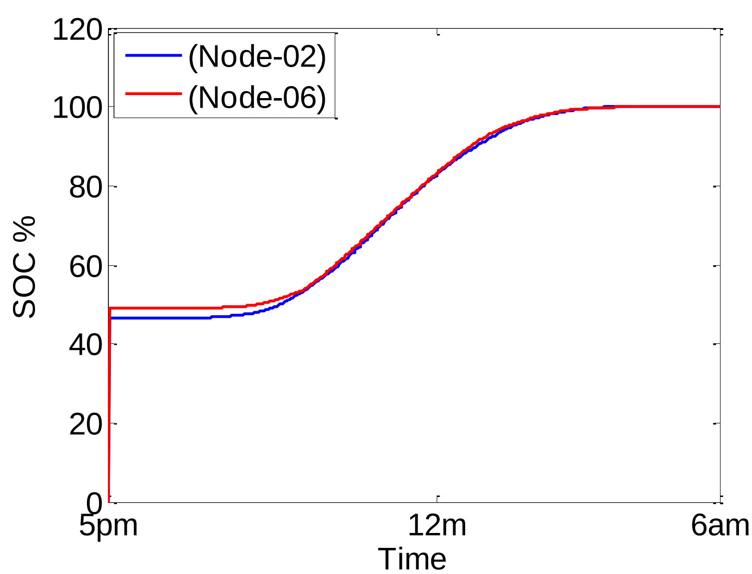

Figure 6- 10 Average charging rate at node 2 and node 6 in case of VR at node 5

6.2 Coordination with Capacitor Banks

A shunt capacitor generates reactive power to compensate the reactive power demand and thereby boosts the voltage. Shunt capacitors can be installed in the substation (which can be called substation capacitors) or along the feeder (i.e. feeder capacitors) [63].

In order to properly compensate the varying reactive power demand, the shunt capacitor (SC) may need to be switched on at the maximum load and to be switched off at the minimum load. When the load varies during the day, the switched capacitors should be properly controlled. Different conventional controls can be used to control switched capacitors, such as time, voltage and reactive power. Time controlled capacitors are especially applicable on feeders with typical daily load profiles where the time of the switching-on and off of the shunt capacitor can be predicted. The main disadvantage of this control is that the control has no flexibility to respond to load fluctuation caused by weather, holidays, etc. Voltage controlled capacitors are most appropriate when the primary role of the capacitor is for voltage support and regulation. Reactive power controlled capacitors are effective when the capacitor is intended to minimize the reactive power flow [16].

This work utilizes the voltage controlled shunt capacitors. The voltage controlled shunt capacitors are switched on when the measured voltage is less than the desired value beyond the specified bandwidth / dead band.

6.2.1 Simulation Results

The capacitor banks are connected to either node 2 or node 5. As in [16], the total available capacity is assumed to be 1 MVar for each of the nodes. For node 2 each capacitor step is assumed to be 0.1 MVar which causes a voltage change of about 0.007 per unit. For node 5 each capacitor step is taken to be 0.1 MVar also.

The settings of the shunt capacitor are the following

Voltage Set point

It is the voltage which the utility desired to maintain at the node. For this study it is selected as 0.99 per unit. We should note that this is different from the controller set point which is 0.955. Also, the controller set point is constant through the entire simulation.

Step Capacitor

It is the amount of reactive power injected by one shunt capacitor. The resultant voltage change can be termed as step voltage. For both node-2 and 5, it is 0.007 per unit.

Bandwidth

It is the amount of variance allowed in voltage before injecting capacitor bank. This is selected equal to step voltage.

Figure 6-11 – Figure 6-15 show the results in case of shunt capacitor connected to node 2. As in the case of adding a VR at node 2, adding a shunt capacitor shows a similar effect.

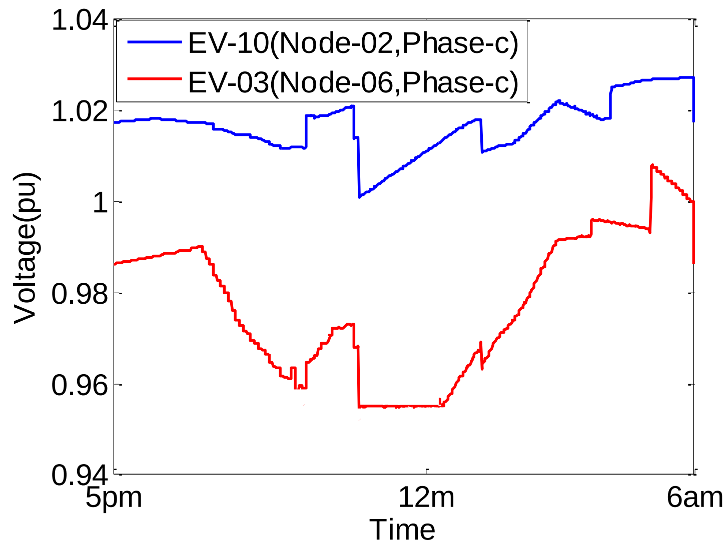

Figure 6- 11 Voltage profiles for POCs A's and B's EVs in case of SC at node 2

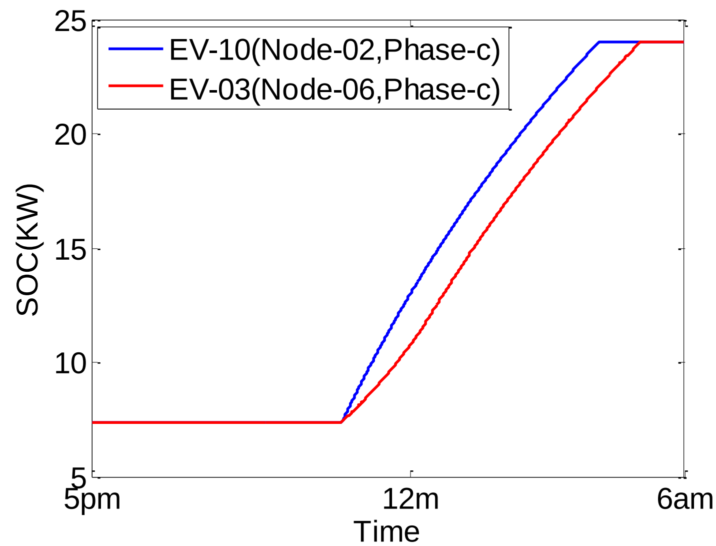

Figure 6- 12 SOC for POCs A's & B's EVs in case of SC at node 2

Figure 6-11 shows the voltage of the upstream node 2 which is already close to or above the set point voltage 0.99. So there is no much change in the number of the capacitor bank steps. Figure 6-13 shows this slight change in the number of steps where the maximum change is equal to 2 steps only.

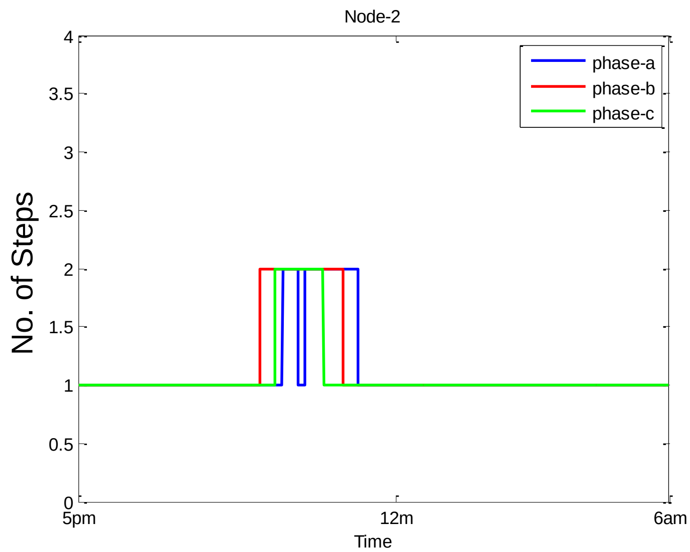

Figure 6- 13 Shunt Capacitor steps at node 2

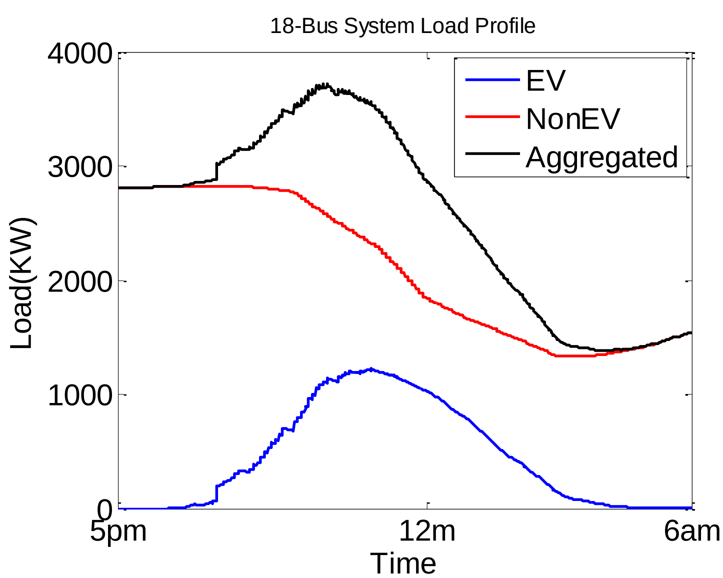

Figure 6- 14 EV, Non EV and Total loads for the distribution system in case of SC at node 2

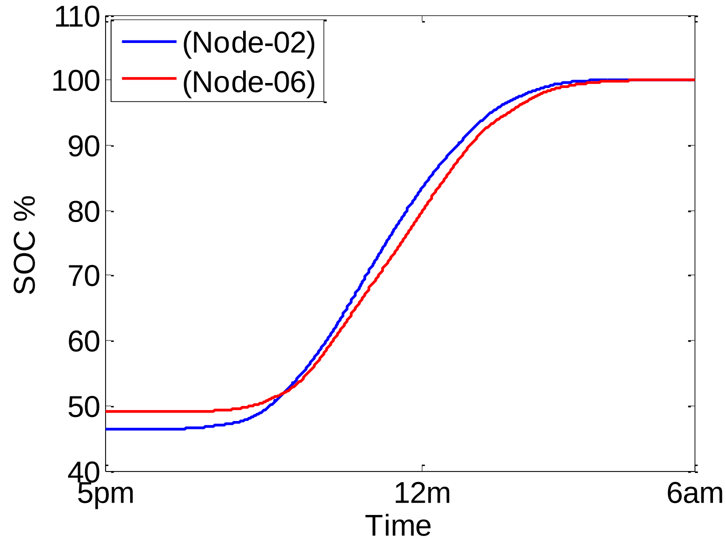

Figure 6- 15 Average charging rate at node 2 and node 6 in case of SC at node 2

Figure 6-16 – Figure 6-20 show POC A's and B's voltage profiles and their SOCs, steps for the capacitor bank at node5, total distribution system load and the average charging rate at node 2 and node 6 in case of shunt capacitor (SC) connected to node 5.

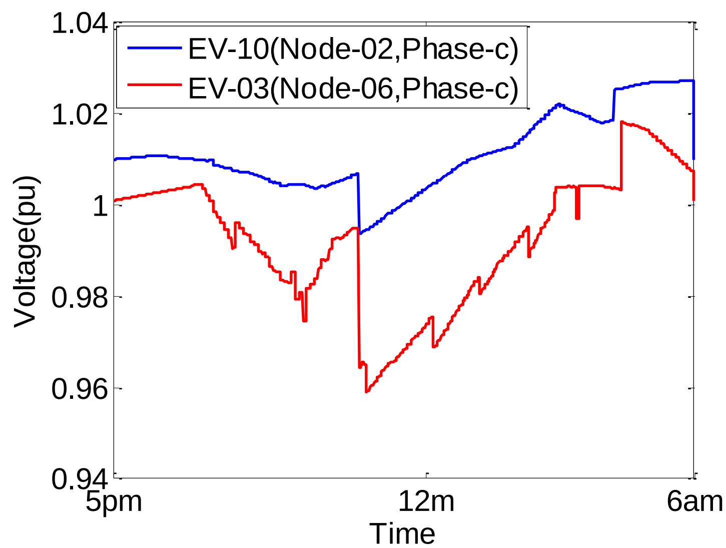

Figure 6- 16 Voltage profiles for POCs A's and B's EVs in case of SC at node 5

Figure 6-16 clearly shows that adding capacitor at node 5 will increase the voltage at the downstream nodes 6, 7, 8. In our case, the voltage at house 3 at phase C of node 6 is shown. Figure 6-17, Figure 6-20 show the effect of enhancing the voltage which results in increasing the charging rate at the downstream houses, so POCs A's and B's EVs almost finish charging at the same time.

Number of steps required to maintain the voltage at 0.99 is smaller compared to the number of taps in case of voltage regulator. This comes from the fact that adding shunt capacitor step will increase the voltage by .007 while the tap of voltage regulator will increase the voltage by 0.003125.

Figure 6-18 shows the change in the number of steps of the shunt capacitor. The shunt capacitors are utilized to their maximum in the period of intense EV charging and heavy Non-EV loading and then the capacitors gradually switched off.

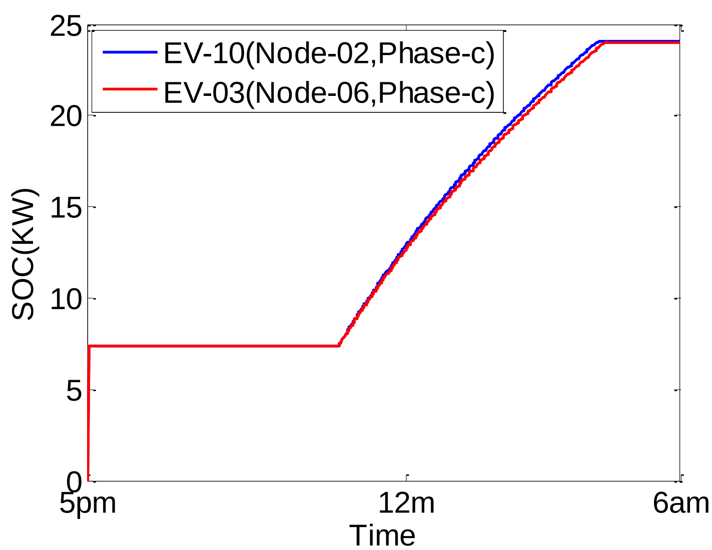

Figure 6- 17 SOC for POCs A's & B's EVs in case of SC at node 5

Figure 6-19 shows EV, Non EV and Total loads for the distribution system in case of SC at node 5.

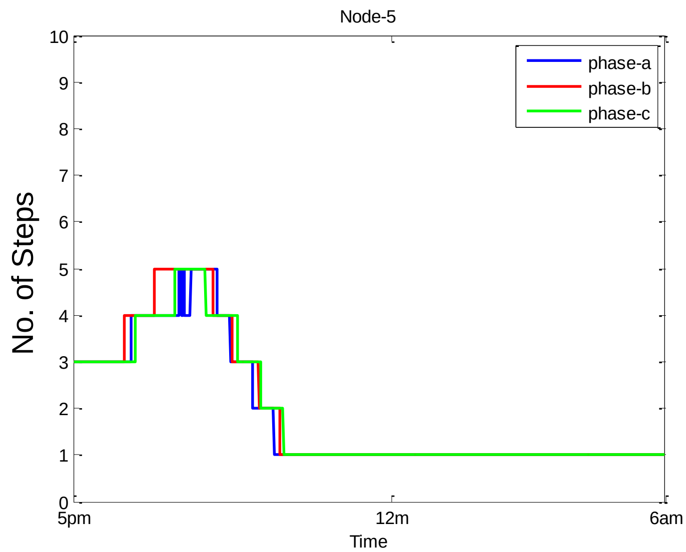

Figure 6- 18 Shunt Capacitor steps at node 5

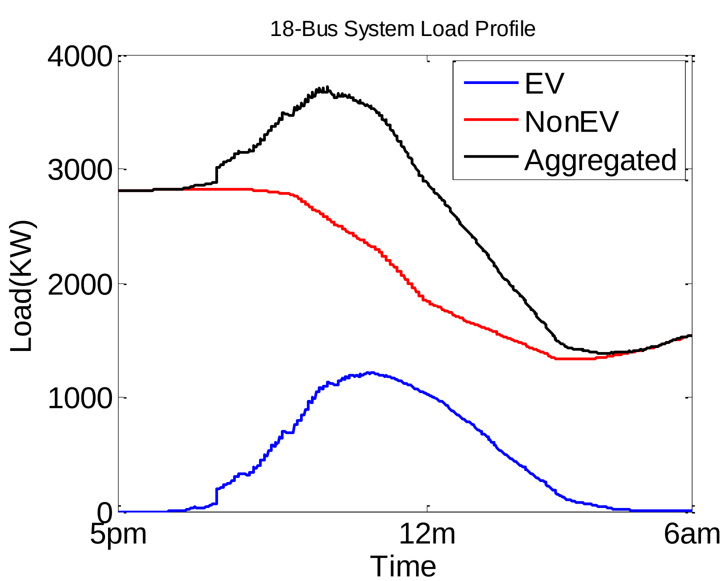

Figure 6- 19 EV, Non EV and Total loads for the distribution system in case of SC at node 5

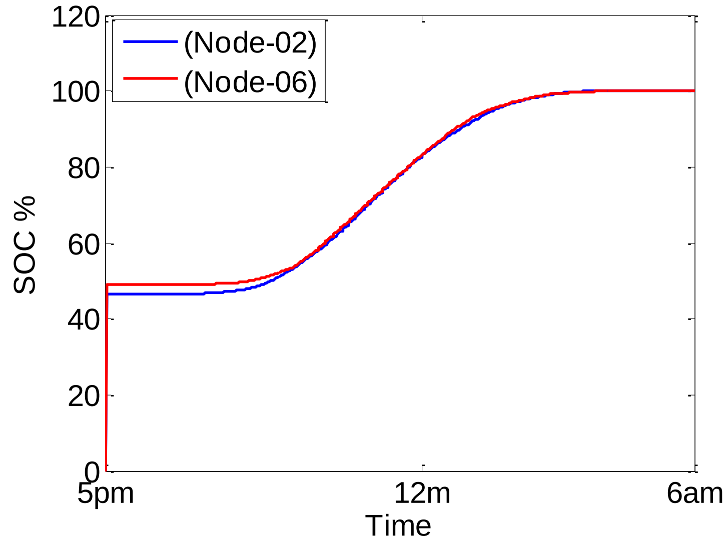

Figure 6- 20 Average charging rate at node 2 and node 6 in case of SC at node 5

Table 6-1 shows the corresponding charging times before and after adding voltage control units at different nodes. The table shows clearly the effect of adding voltage control units, especially at the downstream node.

Table 6- 1 Comparison in terms of time to full charge (in Hrs), SOC-dependent scheme with voltage control devices

Case	Node-02		Node-06	
	POC A	Latest	POC B	Latest
No Voltage Control Devices	5.642	5.708	7.13	7.492
VR at Node 2	5.6583	5.7	6.625	6.833
VR at Node 5	5.7	5.7417	5.875	5.875
SC at Node 2	5.6166	5.6417	6.525	6.525
SC at Node 5	5.7	5.7417	5.875	5.875

CHAPTER 7

CONTROL SCHEME PERFORMANCE IN PRESENCE OF DISTRIBUTED GENERATION UNITS

For decades, the electric power system has been based on centralized generation where a small number of large generation units were used to generate power which is then transferred using the transmission system after being stepped up using transformers.

Over the last few years, a number of factors have been combined to lead to the increased interest in the use of small-scale generation, connected to local distribution systems, which is commonly called Distributed Generation (DG). Environmentally friendly electricity supply, electricity market liberalization, constraints on the construction of new transmission lines, increasing demand on highly reliable electricity supply, and reduction of the usage of fossil fuel resources, are some of benefits that DG can offer [63]. DG can come from renewable or non-renewable energy resources, using both modern and conventional technologies. Figure 7-1 shows the structure of conventional power system and power system with distributed generation units. The presence of the DG, especially when the DG share is significant, will impact the power distribution system operation and control. It is therefore deemed necessary to evaluate the impact of increased DG on the design requirements for distribution systems. Among the different DG technologies, the effect of wind energy will be evaluated in this thesis. Wind energy was choosed due to the high potential of wind energy and its significant share in many countries nowadays.

Also wind is a very variable resource. Solar energy is not investigated here due to the assumption that the electric vehicles are charging according to the time of use tariff where the electricity prices are low during night and the EVs are charging at homes from 6 pm to 6 am.

Different scenario of wind energy will be evaluated in coordination of the proposed controller. The scenarios will vary between installing the wind power at individual houses at the upstream and downstream nodes at different seasons up to increasing the wind penetration level to 20% which is starting to be current share or target in many countries nowadays.

The wind data that are used in this thesis is scaled actual data from Bonneville Power Administration (BPA) which is an American federal agency operating in the Pacific Northwest.

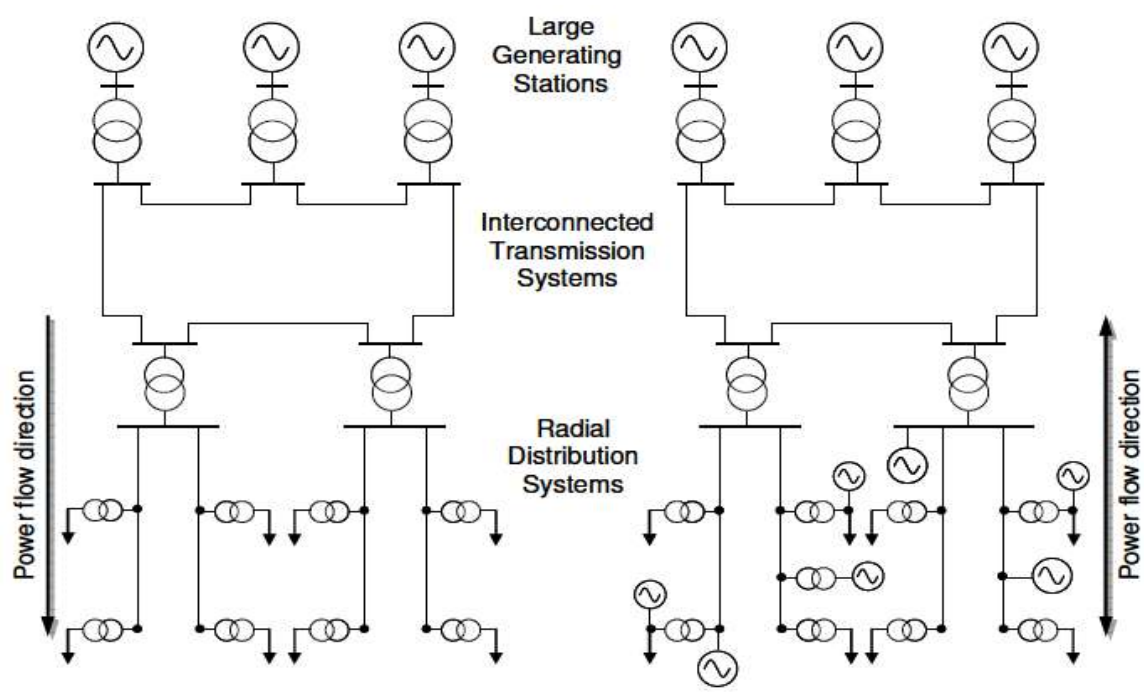

Figure 7- 1 left conventional electric power system, right electric power system with distributed generations [63]

7.1 Effect of Wind Energy on Individual Houses

A small wind turbine is installed at a single house to see the effect of feeding the house from its own generation unit and how this will affect the charging rate of the electric vehicle connected to that house.

For this test the wind turbine is installed either at the downstream house at node 6 ,which suffers from low voltage, or at the upstream house at node 2 which has the highest primary voltage in the system. The test is done for winter and summer scenarios.

7.1.1 Winter Scenario

For this scenario, the wind power data used is shown in Figure 7-2.

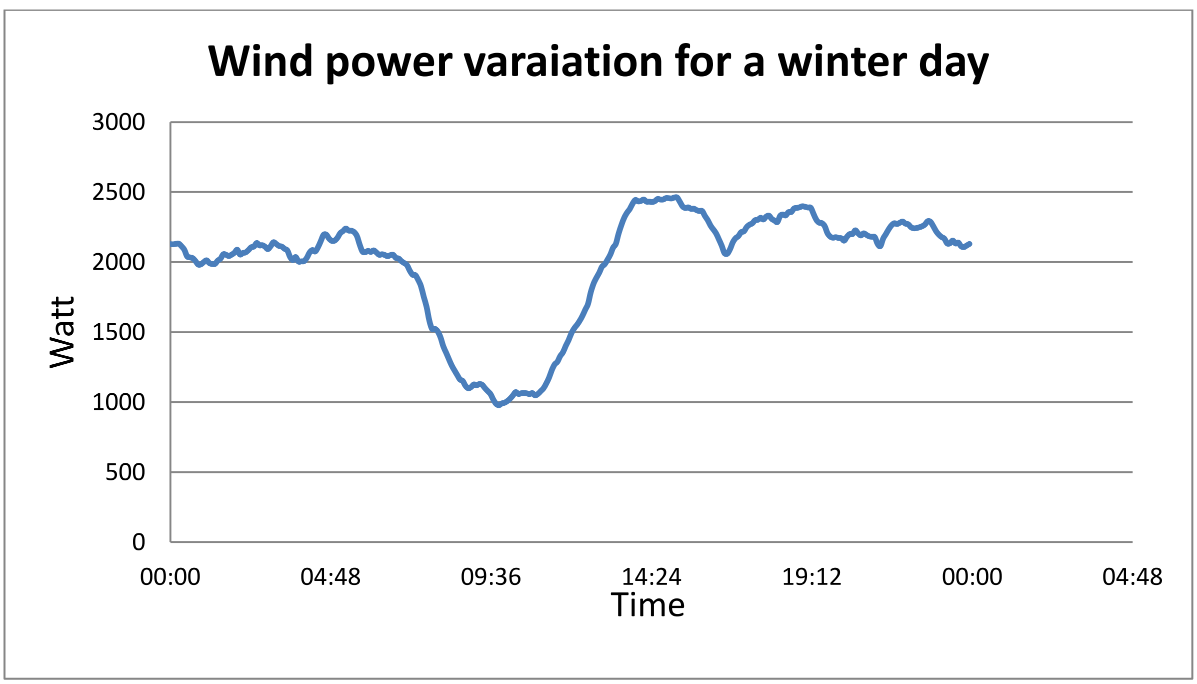

Figure 7- 2 Wind power variations for a winter day

7.1.1.1 Wind Turbine at Downstream House

For this case, the wind turbine is installed at the downstream house at node 6. This house suffers from the lowest voltage in the system and in normal cases, it charges at lower rate compared to the upstream house.

Figure 7-3 – Figure 7-5 show POC A's and B's voltage profiles, their SOCs and the average charging rate at node 2 and node 6 in case of wind turbine (WT) installed at the downstream house. The figures show clearly the effect of installing the turbine at the downstream house at node 6.

Figure 7-3 shows how the voltage is improved by installing the wind turbine. At some points of time, the voltage at that house is higher than that at the upstream node. This is due to the WT feeding that downstream house and the house does not suffer from the voltage drop along the feeder. The improvement in voltage leads to a higher charging rate of the electric vehicle connected to that house.

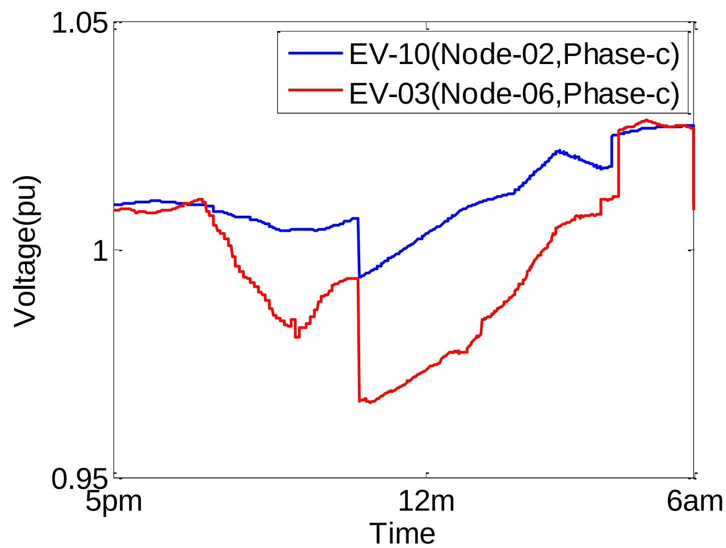

Figure 7- 3 Voltage profiles for POCs A's and B's EVs in case of WT at downstream house for winter scenario

Figure 7-4 shows that the charging rate at the downstream house becomes almost equal to that at the upstream one. However adding a single wind turbine will have no great effect on the other houses since the back feed power from the downstream house to the feeder is very small, if any, compared to the total power of the system. Figure 7-5 shows that there is not great effect on the charging rate of the other EVs in the systems. In other words, DG unit benefits the house it is connected the most to which is very desirable.

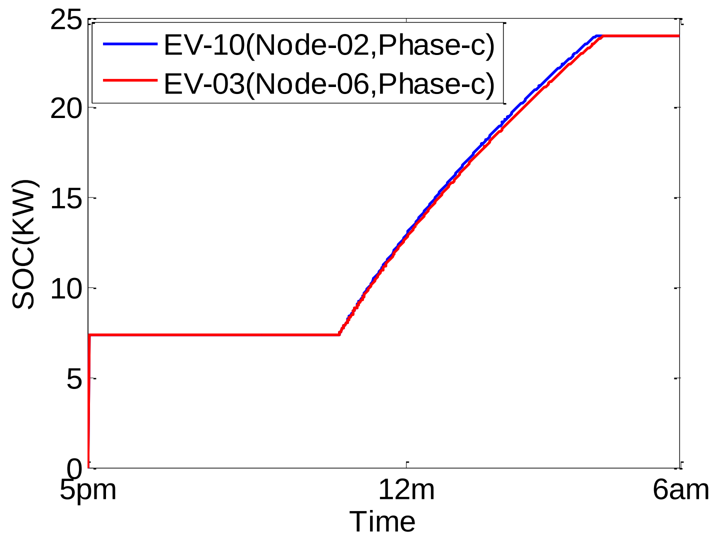

Figure 7- 4 SOC for POCs A's & B's EVs in case of WT at downstream house for winter scenario

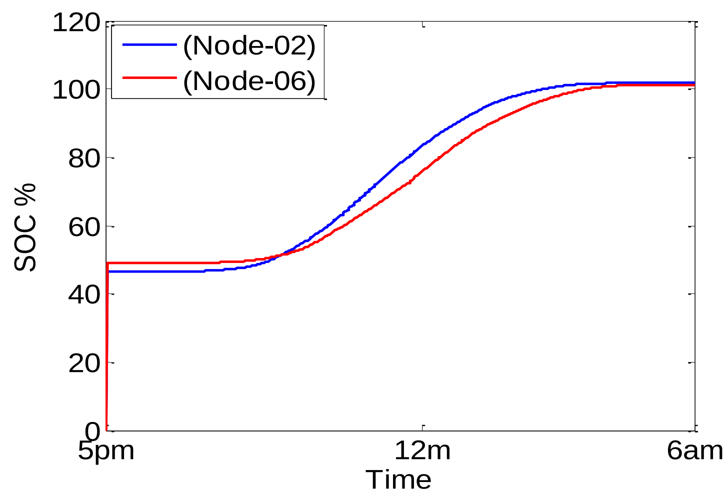

Figure 7- 5 Average charging rate at node 2 and node 6 in case of WT at downstream house for winter scenario

7.1.1.2 Wind Turbine at upstream House

For this case, the wind turbine is installed at the upstream house at node 2. This house has the advantage of being at the highest voltage compared to all other houses.

Figure 7-6 – Figure 7-8 show POC A's and B's voltage profiles, their SOCs and the average charging rate at node 2 and node 6 in case of wind turbine (WT) installed at the upstream house. Since the upstream house is already at the highest voltage point in the system, installing the wind turbine has a small effect on it. This can be shown by comparing Figure 7-6 and Figure 4-15 where it is obvious that there is only a slight improvement in the voltage. Since there is no great improvement in voltage, the charging rate of the upstream electric vehicle is almost the same. This can be shown in Figure 7-7.

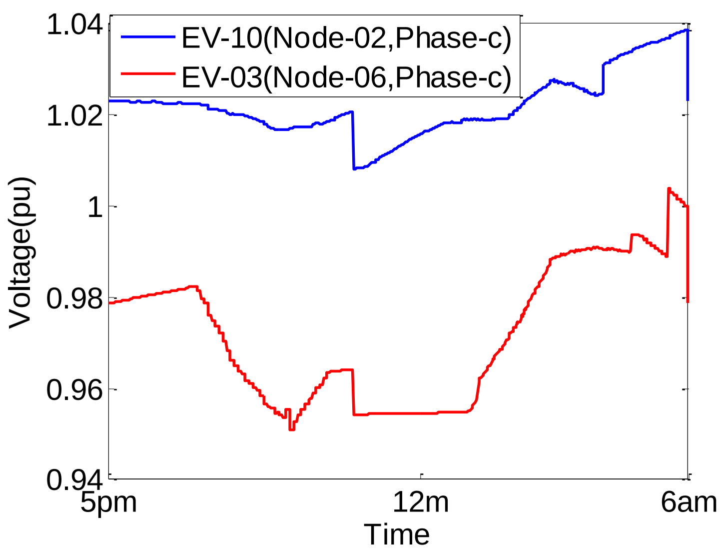

Figure 7- 6 Voltage profiles for POCs A's and B's EVs in case of WT at upstream house for winter scenario

Again, installing a single wind turbine will have no great effect on the other houses since the back feed power from that house to the feeder is so small compared to the total power of the system. Figure 7-8 shows that there is not great effect on the charging rate of the other EVs in the systems.

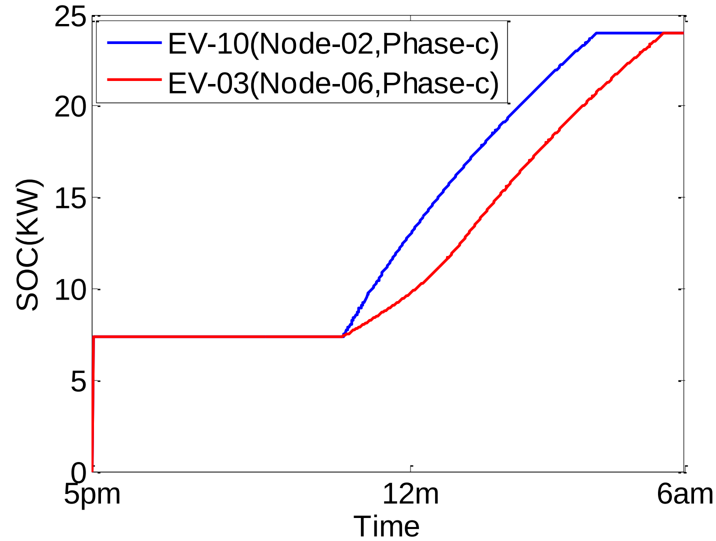

Figure 7- 7 SOC for POCs A's & B's EVs in case of WT at upstream house for winter scenario

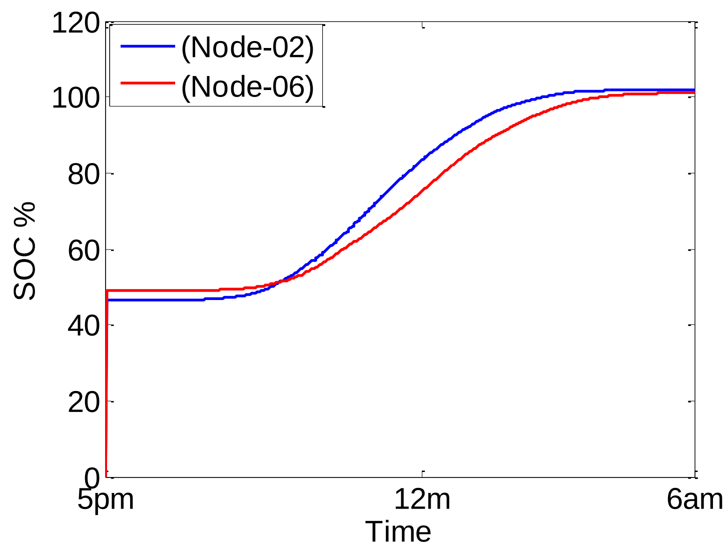

Figure 7- 8 Average charging rate at node 2 and node 6 in case of WT at upstream house for winter scenario

7.1.2 Summer Scenario

For this scenario, the wind power data for a summer day from BPA data is shown in Figure 7-9.

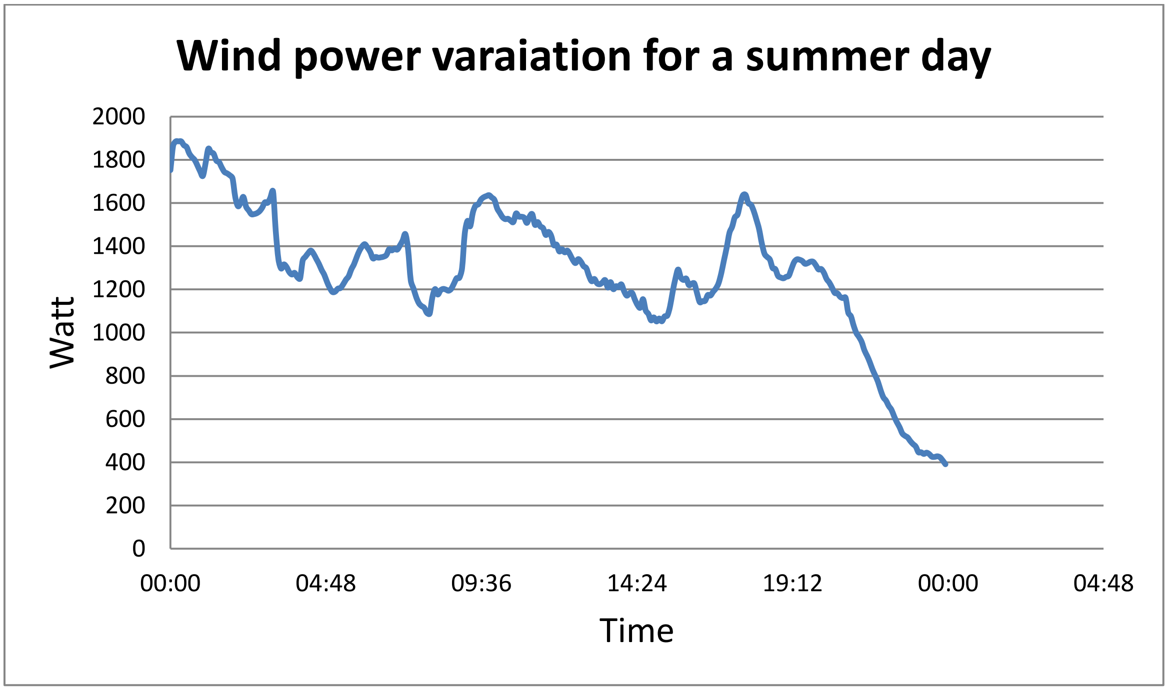

Figure 7- 9 Wind power variations for a summer day

7.1.2.1 Wind Turbine at Downstream House for Summer Scenario

Figure 7-10 – Figure 7-12 show POC A's and B's voltage profiles, their SOCs and the average charging rate at node 2 and node 6 in case of wind turbine (WT) installed at the downstream house for summer scenario. The figures show clearly the effect of installing the turbine at the downstream house at node 6.

Figure 7-10 shows how the voltage is improved by installing the wind turbine. At some points of time, the voltage at that house is higher than that at the upstream node. This is due to the WT feeding that downstream house and the house does not suffer from the voltage drop along the feeder. The improvement in voltage leads to a higher charging rate of the electric vehicle connected to that house. However this improvement in voltage is less than the improvement in case of the winter scenario. This is because the available wind power in summer is less the power available in winter.

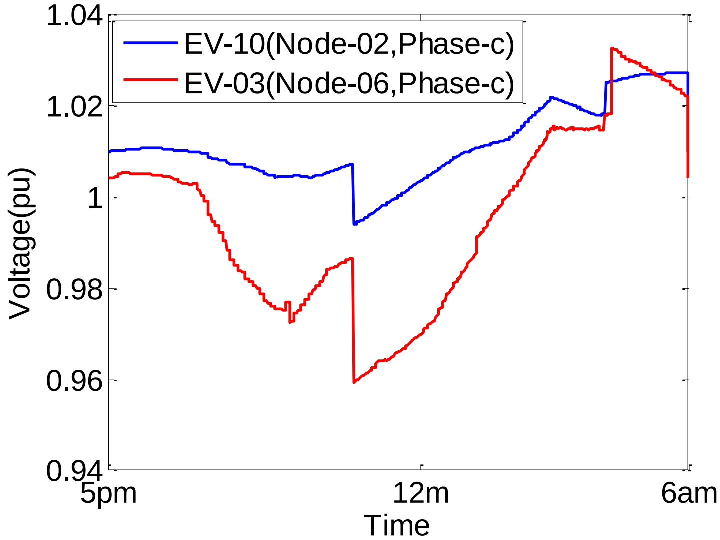

Figure 7- 10 Voltage profiles for POCs A's and B's EVs when WT at downstream house for summer scenario

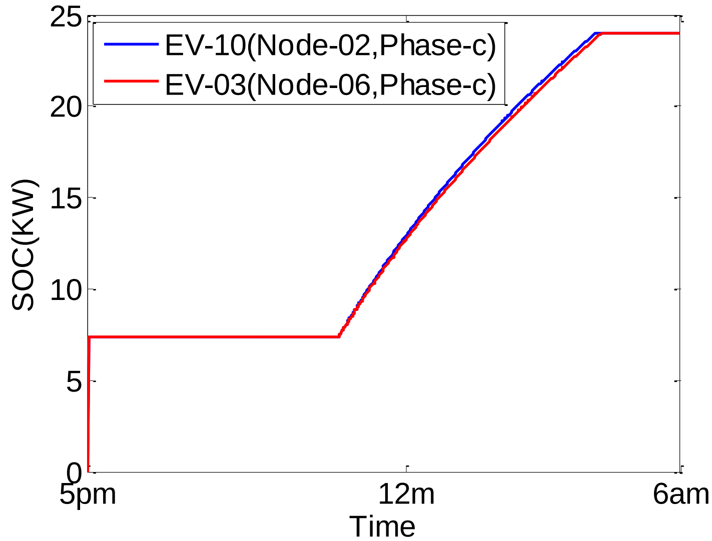

Figure 7- 11 SOC for POCs A's & B's EVs in case of WT at downstream house for summer scenario

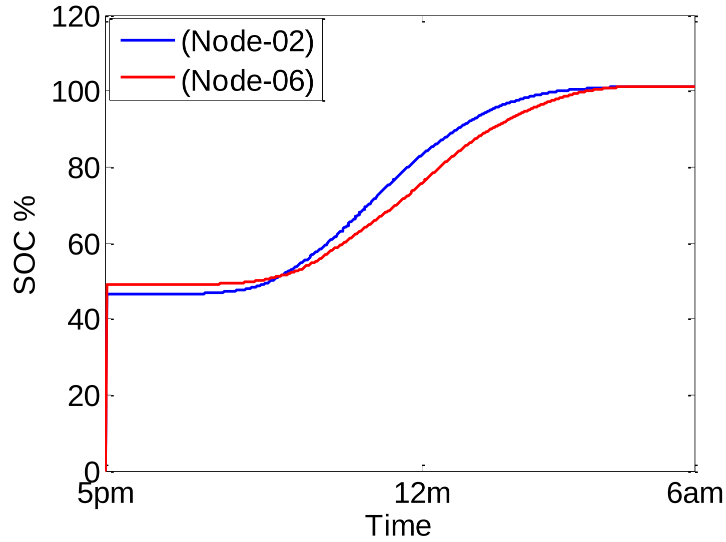

Figure 7- 12 Average charging rate at node 2 and node 6 when WT at downstream house for summer scenario

Figure 7-11 shows that the charging rate at the downstream house becomes almost equal to that at the upstream one. However adding a single wind turbine will have no great effect on the other houses since the back feed power from the downstream house to the feeder is so small compared to the total power of the system. Figure 7-12 shows that there is not great effect on the charging rate of the other EVs in the systems.

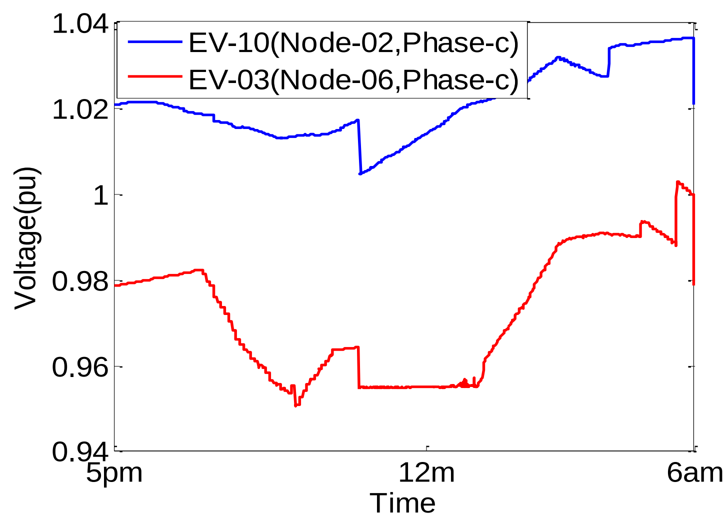

Figure 7- 13 Voltage profiles for POCs A's and B's EVs when WT at upstream house for summer scenario

7.1.2.2 Wind Turbine at Upstream House for Summer Scenario

Figure 7-13 – Figure 7-15 show POC A's and B's voltage profiles, their SOCs and the average charging rate at node 2 and node 6 in case of wind turbine (WT) installed at the upstream house for summer scenario. Since the upstream house is already at the highest voltage point in the system, installing the wind turbine has a small effect on it. This can be shown by comparing Figure 7-13 and Figure 4-15 where it is obvious that there is only a slight improvement in the voltage. Since there is not a great improvement in voltage, the charging rate of the upstream electric vehicle is almost the same. This can be shown in Figure 7-14.

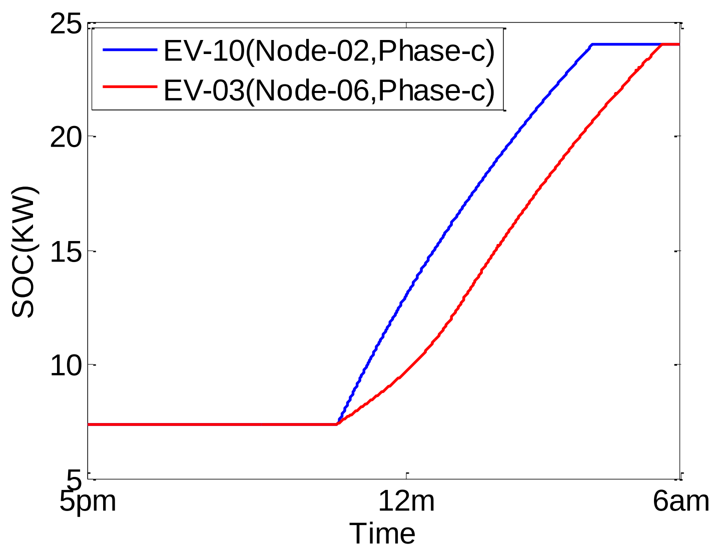

Figure 7- 14 SOC for POCs A's & B's EVs in case of WT at upstream house for summer scenario

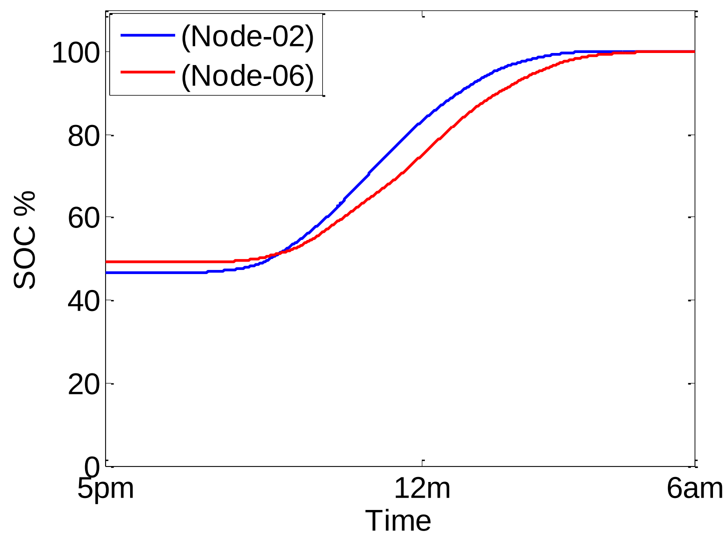

Figure 7- 15 Average charging rate at node 2 and node 6 when WT at upstream house for summer scenario

7.2 Effect of Wind Energy in Case of 20 % of the Houses with WT

For this test, small wind turbines are installed at different houses selected randomly. The number of houses selected represents 20 % of the total number of the houses. This is to indicate the effect of 20 % penetration level of wind turbines which is currently exist in many countries. The wind power data is the same for all houses since it is the normal case that the houses connected to the same feeder exist in the same geographical area, hence they will see more or less the same weather and the same wind variations. For this test, winter data is used.

Figure 7-16 – Figure 7-19 show POC A's and B's voltage profiles and their SOCs, total distribution system load and the average charging rate at node 2 and node 6 in case of wind turbines (WTs) installed at 20% of the houses for winter scenario.

It is obvious from the figures that with 20% of the houses having wind turbines, the voltage has greatly improved. This improvement in voltage increased the charging rate at both the up and downstream houses but it is more obvious for the downstream house since it is the one which suffers from low voltage. This can be seen in Figure 7-17.

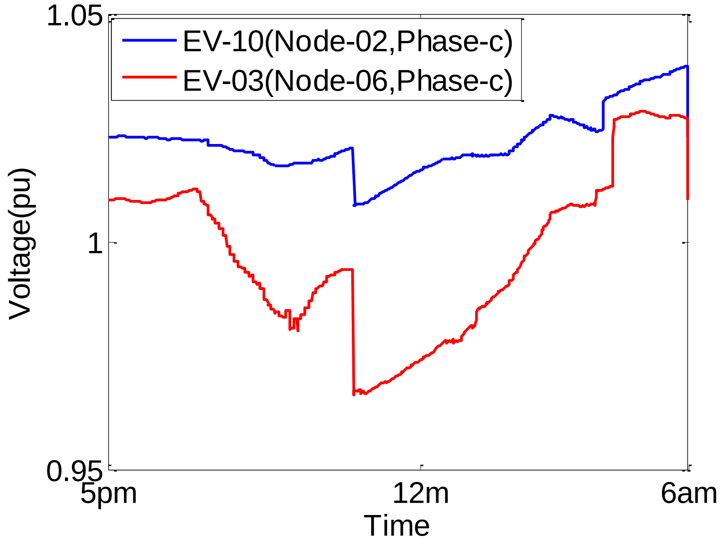

Figure 7- 16 Voltage profiles for POCs A's and B's EVs when WTs installed at 20 % of the total houses

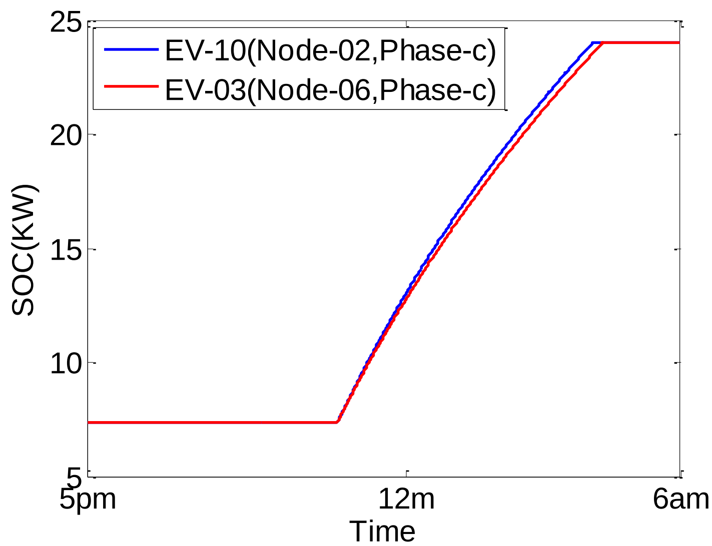

Figure 7- 17 SOC for POCs A's & B's EVs in case of WTs installed at 20 % of the total houses

Unlike the previous cases, this level of wind power will affect all houses, not only the houses at which the turbines are installed. This is due to the improvement of the whole system voltage. Figure 7-19 shows that by increasing the level of wind power, the average charging rate of the electric vehicles will increase. This can be clearer by comparing Figures 7-19 with 20% wind power and 4-19 where no wind turbines are installed.

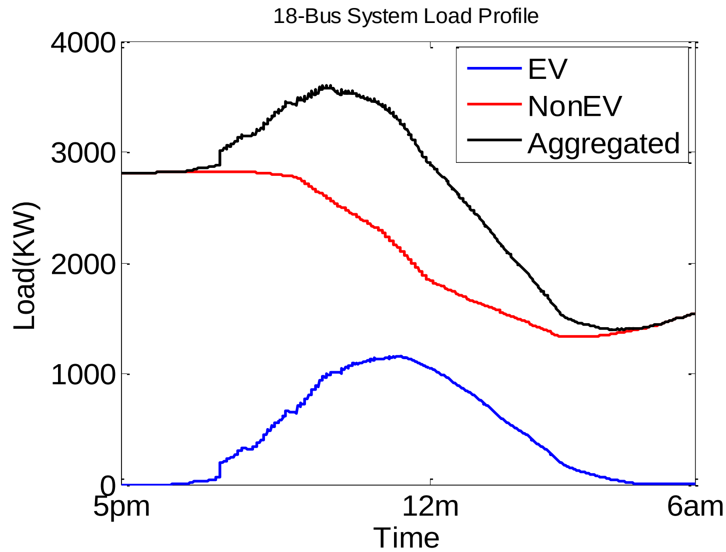

Figure 7- 18 EV, Non EV and Total loads for the system in case of WTs installed at 20% of the total houses

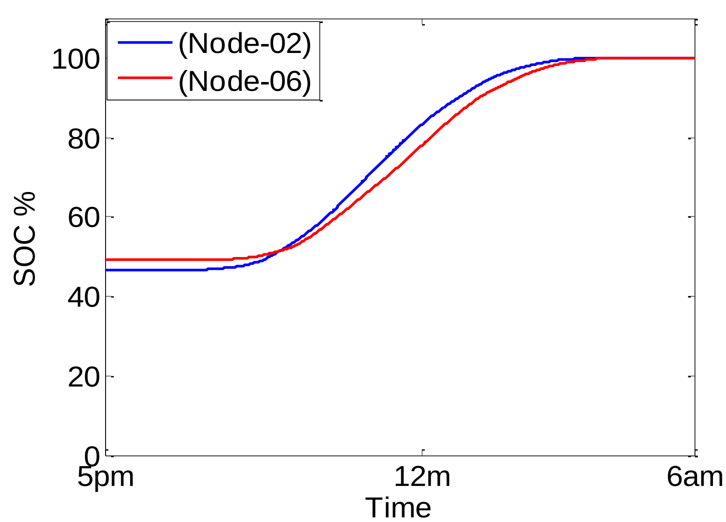

Figure 7- 19 Average charging rate at node 2 and node 6 when WTs installed at 20 % of the total houses

CHAPTER 8

CONCLUSION AND RECOMMENDATIONS

The thesis has proposed an effective practical communication-free voltage feedback control EV charge strategy. The control technique uses variable gain to ensure fairness among the different electric vehicles connected at different parts of the system as well as commitment with the voltage constraint regulation in the distribution system. This control scheme, though requires no real-time communication, effectively coordinates charging among the EVs connected to the distribution nodes in a fair manner so that voltage violations are avoided. The voltage set points for the controller are fixed and do not need to be modified due to seasonal variations. This is a good property of the controller since once the gains are set, there is no need to change them or to change the set points. In addition to the local voltage level, the proposed scheme takes into account the battery SOC and the EV owner's preference (if any) of end-of-charge time. Several of the practical considerations on the distribution system were addressed. These include different loading conditions and system reconfiguration. The simulation results show the robustness of the controller under different conditions varying from light loading condition to normal loading and from simple reconfiguration to significant reconfiguration. Moreover, the results show the effectiveness of the controller in the presence of voltage control units connected to the system such as voltage regulators and capacitor banks. Also, the controller performed well in the presence of the distributed generation units such as wind turbines.

Although the proposed controller shows robustness and effectiveness, there are several aspects that need to be considered as future work:

1. Testing the controller performance in the presence of a more detailed model of the distribution system up to the appliances level, taking into consideration other controllable loads that can serve in demand side management (DSM).
2. Testing the controller with other hierarchical control algorithms where there can be some signals from the market.
3. The existing strategy deals with unidirectional power flow from grid to EV. It can be extended to implement bi-directional V2G by allowing PD to be negative when measured voltage falls below the reference value contrary to the existing case when PD becomes zero when measured voltage is less than reference voltage.

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