Impact of Energy Management of Electric Vehicles on Transient Voltage Stability of Microgrid

Muhammad Shoaib Khalid1, Xiangning Lin2, Yixin Zhuo3, Ramesh Kumar4, Muhammad Kashif Rafique5
1 School of Electrical and Electronics Engineering, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan, China. email shoaibusmani@hust.edu.cn, xiangning.lin@hust.edu.cn
2 School of Electronics and Computer Engineering, Hanyang University, South Korea.
3 School of Information and Communication Engineering, Sungkyunkwan University, South Korea.

Abstract

There is cause and effect relationship between increase in load due to increasing penetration of electric vehicle load and unbalanced conditions that may lead to further degradation of power quality, voltage problems and even damage the equipment if the system is not properly managed. This paper presents detailed review of energy supply and management in conjunction with load synchronization through EVs for maintaining transient voltage stability by providing reactive power support to the power grid in vehicle-to-grid (V2G) mode of operations. The energy management system is considered at different levels such as, stand-alone PV, stand-alone wind, stand-alone battery storage, stand-alone EV parking lot, residential feeder and commercial building feeders. First we proposed energy management algorithm, to limit the peak power drawn by electric vehicles from distributed energy resources of microgrid, such that additional electrical resource will be transferred to resource constrained devices. The electric vehicles negotiate based on their demand, priority and available electrical resource such that during higher electricity price the higher priority vehicles still require resource and perform uninterrupted operation. The transfer of electrical resource from one load device to another will help in reducing peak demand and improving the efficiency of the system. Secondly we proposed transient voltage stability margin index and test the capability of EVs in contributing storage and supply services to the grid. The energy management control simulations are realized in DIgSILENT Power factory.

Keywords: distribution network reliability, energy management system, vehicle-to-grid (V2G), ancillary services

1 Introduction

Electric vehicles have been developed and marketed since the end of the 19th century. Energy scarcity and environmental pollution has compelled researchers to develop efficient, environmental-friendly electric vehicles along with the advancement in the clean energy technology [1]. Currently the penetration of electric vehicles load is less than the expected but in near future it is expected that the use of electric vehicles will rise.
Moreover it is expected that there will be more and more induction motor loads connected to the power grid. The motor loads are random and have fluctuations in the characteristics which have significance impact on grid security [2]. Hence, with the increase in non-linear load the power system optimization control, power quality maintenance and distribution network planning become more difficult. The grid security and stability studies are accomplished to assess the impact of induction motor load growth in terms of grid voltage loss, harmonics and load imbalances and its mitigation using electric vehicles as a provision of ancillary services, such as reactive power compensation, the load support and the frequency tuning [3-5]. Electric vehicles can act a special kind of load and source, which can be supplied power from the grid for charging and take back power when necessary [6]. As a mobile storage unit, EV can be connected to the grid as mobile storage unit and act like a source to provide reactive power compensation in order to improve the grid stability and security [7]. Therefore it has important theoretical and practical significance to study the transient voltage stability of distribution network which may be improved by vehicle-to-grid (V2G) mode of operation.

Several measures have been taken in the recent decades to provide ancillary services by electric services for better stability and reliability to the stressed systems. Distributed control can provide local compensation like power system stabilizers (PSS) are installed in order to damp low-frequency oscillation. The best quality response is expected with local measurements about the dynamics of disturbance. But there are adverse interactions between multiple adjacent areas of the power system or between power electronics and grid, only a global control can provide better control [8, 9]. Similar to wide-area controllers (WACs) microgrid energy supply and management system (ESMS) coordinate the actions of the distributed energy management systems using IEEE 802.11 Wi-MAX [10]. The ESMS receives information/data of different areas in the power system and based on some predefined objective function, sends appropriate control signals to the distributed EMS for enhancing system's dynamic performance [11]. Several researchers have contributed in the area of intelligent systems and autonomous agents, such as [12] uses a general case of using agent in control systems, [13] motivates the uses of agents at different control levels e.g. feeder and load agents. Whereas, in [14] the multiagent mechanism for islanding operation is depicted. Wide area signal based intelligent control for FACTS have been presented in [15]. Most of the studies mentioned so far have considered conventional power system and some of them have focused the renewable sources but 1) the effects of bidirectional power flows introduced in the case of electric vehicles for the stability of the power system, 2) taking motor load into consideration for transient stability of the power system, 3) load synchronization for steady state response of the system and 4) the role of energy management system in improving the stability of the system are not yet reported.

In this study, 1) the impact of charging and discharging cycles of the electric vehicle (connected to a CERTS microgrid) on the improvement of transient voltage stability of the microgrid in grid connected and islanded mode is presented. 2) An energy management algorithm is developed to balance the load among different types of loads at demand side in microgrid such that additional electrical resource will be transferred to resource constrained devices. The energy management control is implemented in DLgSILENT Powerfactory. The results with and without energy management system for moderate disturbance due to the start of the motor load like a sudden discharging of the EV and also for some extreme situation like sudden transition from discharging to charging mode or a three phase fault during charging or discharging cycle are presented. The analysis show that the electric vehicles connected to the power system and the use of energy management system improves the stability of the system significantly.

The primary contributions of this study are:

- Demonstration of energy management simulation model.
- Illustrating the impacts of EV operations on the stability of the system.
- The design of energy management control for improving the stability of an integrated power system.

Rest of the paper is organized as follows: Section 2 describes the simulation model of CERTS microgrid/ power distribution network architecture. Section 3 illustrates the load synchronization algorithm; Section 4 indicates the the co-simulation platform for energy management system, Section 5 explains a case study and simulation analysis and results, and the last Section 6 shows the conclusion and future research directions.
2 Network architecture

Simulations are performed for a medium voltage distribution network with a nominal voltage of 20 kV. The microgrid adopts CERTS microgrid architecture as shown in Figure 1, which contains four radial feeders, feeder A, feeder B, feeder C, and feeder D. The CERTS microgrid has two critical components, the static switch and the microsource. The static switch has the ability to island the microgrid in case of disturbance in less than a cycle [16] and reconnect when the tripping event is no longer present. In order to prove the effectiveness of the microgrid reconfiguration we have added four backup lines BC1, BC2, CD1 and CD2, these four lines normally disconnected during grid connected mode [17].

Feeder A contains residential subscriber loads containing ordinary loads (about 50% induction motor load), static loads and charging pile for charging of electric vehicles. Charging pile is suitable for charging of electric vehicles at small scale at slow charging rate, while feeder B, feeder C, and feeder D are commercial building subscriber loads which contain less-sensitive loads (about 65% induction motor load) and static loads, ordinary loads (about 50% induction motor load) and static loads, and sensitive loads (about 75% induction motor load), static loads and charging station for the charging of electric vehicles. Charging stations are suitable for charging of electric vehicles at large scale, having the capability of quick charging.

Switch power plant is deployed at the medium voltage bus bar which has the capability to accommodate bulk of electric vehicle for quick charging. The charging pile, charging station and switch power plant employ power electronics controllers that interface the electric vehicle to the grid. These controllers include on board ac to dc converter which is coupled to the grid with a single or three phase connector. The converter has dual functions as diode bridge rectifier for charging the battery or a switch-mode converter which not only controls the charging of the battery, but also have the capability of feeding power from the vehicle to grid (V2G) in regeneration mode [18]. The electric vehicle can contribute to supply storage and supply services to the grid for transient voltage stability.

Stand-alone PV, Wind and battery storage are also connected to the medium voltage bus bar. Whereas, stand-alone battery storage is important to provide transient stability in islanding mode, stand-alone PV modules and wind power to get benefits of renewable energy and synchronous generators necessary for stable operation of microgrid in islanded mode. Batteries and synchronous generators are the two types of sources which may use the droop control for normal operations.

The sensitive loads are supplied through more stable source like synchronous generator due to very high power quality of sensitive loads, while less-sensitive loads may be supplied through both synchronous generators and photovoltaic system (PV). The ordinary loads may or may not have the local generation. Moreover sensitive and less sensitive loads are controllable loads while the ordinary loads are non-controllable loads. The non-controllable loads are supplied from the power commands through the load profile of grid, while the controllable loads are supplied from the power commands through the load profile of DERs in microgrid using ESMS [17].

Controllable and non-controllable loads are further classified as shiftable and non-shiftable loads. Where, shiftable loads follow the smart pricing provided by the power grid/microgrid ESMS and non-shiftable loads cannot follow power grid/microgrid ESMS. In the context of shiftable and non-shiftable loads, loads of different characteristics are available. For example;

Simple timed loads, which are shiftable loads. The user can specify their power rating, run time and desired window time in which they run. The time can be chosen by the user or by the ESMS.

Setpoint based operating loads, which are non-shiftable loads. The user or the ESMS can specify the setpoint that the device must meet.
Dynamic loads are shiftable loads. These loads can be activated multiple times at different instances during a day or multiple loads can be activated together at the same instance of time like electrical vehicles (EV). In our microgrid EV does not stand for a single vehicle only, but rather for any number of charging instances also. The important parameters of EV charging are given in Table 1.

Table 1: Parameters of EV charging

| Nissan LEAF (Electric Vehicle) | Battery Capacity | E<sub>cap</sub> | 24kWh |
| Final SOC | E<sub>final</sub> | E<sub>max</sub> | |
| Minimum SOC | E<sub>max</sub> | 30% |
| Maximum SOC | E<sub>max</sub> | 80% |
| EV Plug-in Time (T<sub>Initial</sub>) | T<sub>rec</sub> | 11 pm |
| EV Plug-out Time (T<sub>Final</sub>) | T<sub>charged</sub> | 7 pm |
| Initial SOC | E<sub>initial</sub> | 40% |
| Charger Rating | P<sub>charge</sub> | 30kW |
| Vehicle to Grid Rating | P<sub>V2G</sub> | 0 kW |
| Delay Time Setting | 12 am |
| Co-efficient to Reduce Peak Power | R<sub>t</sub> | 0.0004 |

The ESMS is not only connected to the power grid/microgrid DERs but also with a combination of fixed WiMAX and LAN. The ESMS of each unit has the capability to communicate with each other, as well as between the central microgrid EMS and other EMS units within the microgrid. In the next sub-sections we discuss the mathematical modeling of wind turbine generator, photovoltaic cell, battery storage, diesel generator, induction motor and electric vehicle charging.

### 2.1 Wind turbine generator model

Power output of wind turbines depends on wind speed. Mechanical energy of the wind is converted into electrical energy, the relationship between wind speed and the wind turbine output power \( P_{wt} \) is expressed in term of the following functions given in Equation 1;

\[
P_{wt}(t) = \begin{cases} 
0 & v \leq v_n \\
\frac{P_{wt}}{v_n} (v - v_m) & v_m < v \leq v_r \\
\frac{P_{wt}}{v_n} & v_r < v \leq v_{cut} \\
0 & v > v_{cut}
\end{cases}
\]  

Where \( P_{wt} \) stands for the wind turbine rated power, \( v_m \) stands for the cut-in speed, \( v_r \) stands for the rated wind speed and \( v_{cut} \) stands for the cut-out wind speed. Relationship between the output power and wind speed is represented by Figure 2.

![Figure 2: Wind generator active power output curve](image)

### 2.2 Photovoltaic cell model

The output power of photovoltaic cell is easily affected by the radiation intensity, environment temperature, and factors like shadows, clouds, etc. In this paper, the photovoltaic cell output only considers the effects of irradiation intensity and ambient temperature as shown by Equation 2;

\[
P_v = P_{STC}G_v[1+k(T_c-T_{STC})]/G_{STC}
\]  

Where \( G_v \) stands for the light intensity of work points \( G_{STC} = 1kW/m^2 \); \( P_v \) stands for photovoltaic output power, \( P_{STC} \) stands for photovoltaic power rated power, \( T_c \) stands for the battery surface temperature \( T_{STC} = 25^\circ C \); \( k \) stands for the temperature coefficient of the power.

### 2.3 Storage battery model

The excessive energy from renewable resources is stored in the battery and when there is inadequate energy generated by the renewable resources battery discharges and provides continuous energy. Battery plays a very important role in islanded mode of operations. According to the energy conservation law, storage batteries charge and discharge cycles satisfy the following Equations.

\[
E_{BAT}(t) = E_{BAT}(t-1)(1-\sigma) + P_{BAT+C}(t)\eta_r
\]

\[
E_{BAT}(t) = E_{BAT}(t-1)(1-\sigma) + P_{BAT-D}(t)\eta_d
\]  

Where \( P_{BAT+C}(t) \) is the period \( t \) to the outside of the battery charge and discharge system power, \( \eta_r \) \( \eta_d \) is the charge and discharge
efficiency of the battery, $\sigma$ is storage battery drain rate (%/h).

2.4 Diesel generator model

The period $t$ in diesel generator for fuel consumption is given by following Equation 4.

$$V_{fuel}(t) = \xi_{fuel}P_{engine}(t)$$

Where $V_{fuel}(t)$ is diesel generator fuel consumption period $t$, $P_{engine}(t)$ is the diesel generator output power period $t$, $\xi_{fuel}$ is diesel fuel factor L/kWh.

2.5 Induction motor load model

The power system integrated load model is comprised of induction motor in conjunction with the static load that can be representation of actual dynamic load [19]. This paper considers slip index of the induction motor for transient voltage stability margin index. The value of slip index is based on either the clearing time of small disturbance or by the reactive power support by the available electric vehicles. It is a measure of voltage induced by the stator to the rotor of induction motor during the fault/disturbance. The slip $s$ of an induction motor is the difference between the synchronous speed and the rotor speed, expressed as a per-unit of synchronous speed [20] and the slip-torque characteristics are given in [21].

2.5.1 Impact of induction motor on transient voltage stability margin in distribution network

Short term interference in voltage mainly refers to dynamic load stability analysis. Dynamic load especially induction motor load has the greatest impact on the transient voltage stability. In extreme conditions it may cause a larger voltage collapse. We consider the dynamic role of induction motor load in perspective of transient voltage stability. It is necessary to study the transient behaviour of the turbulent induction motor connected to the power grid in order to determine the power grid transient stability. The transient voltage stability margin index can be explained as follows; 1). The slip $s$ can be characterized as a measure of transient voltage stability margin index [20].

$$s = n_s - n / n_s$$

Where $s$ is the slip, $n_s$ is the synchronous speed (r/min) and $n$ is the rotor speed (r/min). The slip is practically zero at no load and is equal to 1 when the rotor is locked.

2). If $S_{scm}$ represents non-steady state slip (at minimum voltage) and $S_{max}$ the maximum value of induction motor slip (at clearing time), then the transient voltage stability margin index can be represented as following in Equation 6.

$$\eta = \frac{S_{scm} - S_{max}}{S_{scm}}$$

(6)

2.6 Electric vehicle charging

Different kind of batteries can be employed with the electric vehicles such that lead acid, nickel cadmium and lithium ion etc. The lithium ion batteries are preferred due their higher energy density and their capability of less self-discharging [22]. Moreover different types of chargers can be employed such as high frequency switching (HFS) chargers and phase control (PC) chargers. HFS is preferred for charging at power factor above 0.9; lower harmonic pollution, higher efficiency and fast dynamic response as compared to PC. EV charging has three modes, modes of slow (L1), routine (L2), and fast (L3) charging. These modes have five parts as shown in Table 2.

<table>
<thead>
<tr>
<th>Charging Modes</th>
<th>Nominal Voltage (V)</th>
<th>Nominal Current (A)</th>
<th>Nominal Active Power (KW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>Single-phase</td>
<td>220</td>
<td>16</td>
</tr>
<tr>
<td>L2</td>
<td>Three-phase</td>
<td>220</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>2-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Three-phase</td>
<td>380</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>2-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Three-phase</td>
<td>380</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>2-3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L3</td>
<td>600</td>
<td>300</td>
<td>180</td>
</tr>
</tbody>
</table>

Table 2: EV charging modes

Development of charging stations is one of the necessary conditions for the wide spread of electric vehicles. The electric vehicle charging may be divided into three categories containing charging pile, charging station and switch power plant as shown in Table 3.

Although charging piles belongs to the residential users but considering the popularity of the electric vehicles the impact of charging pile cannot be ignored for the transient stability of the distribution network. The operation of charging pile is different
from the other household electrical appliances due to the load aggregation. The penetration of electric vehicles can be defined by the following relation given in Equation 7.

\[
\rho = \frac{P_{ev}}{P_L}
\]  

(7)

Where \(\rho\) is the electric vehicle penetration rate, \(P_{ev}\) is active power demand for the electric vehicles and \(P_L\) is the active power demand for all other load including the induction motor load. The reactive power demand of the electric vehicle follows the relation given below;

\[
Q_{ev} = \frac{P_{ev}}{PF} \sin(\cos^{-1}(PF))
\]  

(8)

Where \(Q_{ev}\) is the reactive power available by the electric vehicle and \(PF\) is the power factor of the electric vehicle charger.

Table 3: Types of EV charging station

<table>
<thead>
<tr>
<th>Type of Charger</th>
<th>Charging Time</th>
<th>Suitability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging Pile</td>
<td>1-6 Hours</td>
<td>Suitable for Residential Parking at Small Scale in Distributed Fashion</td>
</tr>
<tr>
<td>Charging Station</td>
<td>30 Minutes (Approx.)</td>
<td>Suitable for Traffic Intensive Areas/ Highways at Large Scale in Centralized Manner</td>
</tr>
<tr>
<td>Switch Power Plant</td>
<td>5-10 Minutes (Approx.)</td>
<td>Suitable for City Centres/ Highways at Large Scale in Centralized Manner</td>
</tr>
</tbody>
</table>

2.7 Transient voltage stability and research response

In recent years, the induction motor, power electronics and other dynamic load has impact on transient voltage stability of the power distribution network and in future more and more electrical vehicles will be in use and it is expected to build large scale electric vehicles charging stations and they will rely on the power electronics controlled devices connected to the power grid and will be in the grid for providing the base load and reduce the stability of the power system. Contrary to fact, with the use bidirectional battery chargers the electric vehicles can be used in V2G mode as spinning reserve and enhance the stability of the grid. As a matter of fact, if the electric vehicles are considered as load as shown in [23], smaller size electric vehicles are considered as threat to the safety of voltage stability of distribution network.

To mitigate the peak power drawn by electric vehicles we established a load synchronization algorithm. The purpose of the algorithm is to transfer the extra resource on resource constrained loads in the microgrid and limiting the peak power drawn by electric vehicles using energy management system. The load synchronization algorithm is explained in the next section.

3 Load synchronization algorithm for energy management of EV

Considering the network architecture shown in Figure 1 we balance between the shiftable (EV) and non shiftable loads (other loads) by transferring the extra electrical resource to the resource constrained loads using game theoric approach. In which each electrical load plays a non-cooperative game to reach desired optimal point called Nash Equilibrium.

We consider \(N\) loads ‘\(i = (1, 2, 3 ....N)\)’, and time of twenty-four hours ‘\(j = (0, 1, 2, 3 ....24)\)’ to play a non-corporative game for balancing of loads each hour. First we determine total available resource \(R_j\) and fix reference resource \(RR_{ij}\) for each load ‘\(i\)’ at time ‘\(j\)’ based on history data, to give an estimate to energy supply and management system of usual hourly requirement of each load. Second we consider an important parameter resource share ratio \(RS_{ij}\), which is related to predefined percentage of share in \(R_j\). The ESMS allocates the resource \(RA_{ij}\) for every load based on historic resource share ratio \(RS_{ij}\) each hour after calculating \(R_j\). Where resource allocation is given by;

\[
RA_{ij} = R_j \frac{RS_{ij}'}{\sum_{i=1}^{N} RS_{ij}'}
\]  

(9)

After resource allocation we determine surplus or deficiency \(SD_{ij}\) of resource to the load using
Equation 10. Load having more \( RA_j \) reference resource \( RR_j \) has surplus resource \( SD_j \), otherwise deficiency of resource.

\[
SD_j = RA_j - RR_j
\]  

Before re-distribution of resource we add all the surplus resource to get total surplus sum \( TSS_j \), for any stage of time \( j \) and in a similar manner add deficiency of resource to get total deficiency sum \( TDS_j \). Where, \( TSS_j \) is available for auction. We consider that non-shiftable loads have strict resource requirements and shiftable loads have minimum resource requirements. It is important to satisfy non-shiftable loads before re-distribution whereas if the resource cannot fulfill the minimum requirement of shiftable loads, they can be preempted to switch-off. Resource re-distribution \( RD_j \) is calculated after satisfying the non-shiftable loads and iteratively distributes extra resource to resource deficient loads one unit at a time, which is given by Equation 11.

\[
RD_j = \frac{TSS_j}{TDS_j}
\]  

Next we calculate surplus/deficiency reserve after re-distribution \( SRAR_j \) or \( DRAR_j \) for loads \( i \) at time of equilibrium \( T_j \) as given in Equation 12 and Equation 13.

\[
SRAR_j = RA_i - RD_i
\]  

\[
DRAR_j = RA_i + RD_i
\]  

Surplus resource will be distributed it to the high priority devices \( PR_i \). Like if the requirement of setpoint operated devices is not fulfilled they will be considered now, moreover if the resource cannot fulfill the minimum requirement of shiftable loads, they can be preempted to switch-off. Now we calculate the satisfaction level \( SL_j \) of each load by Equation 14;

\[
SL_j = \sum_{i=1}^{N_{PR}} \frac{PR_i \cdot SRAR_j}{RR_j}
\]

Based on resource re-distribution, satisfaction level is calculated after complete resource re-distribution. It defines how much resource a load has received as compared to its reference resource. Strategy that maximizes the satisfaction and payoff for each player is the equilibrium strategy for this stage. It is termed as Nash Equilibrium in game theory. The equilibrium or optimal point is calculated by:

\[
EQ_j = \arg_{T;X} \max SL_j
\]

Equation 15, calculates the expected optimal point after resource distribution and try to give the best response by all players in current stage of the game because at this time no player has benefit to deviate from this point. The idea is not to find a global optimal but rather a local optimal solution.

4 Co-Simulation Platform for Energy Management System

There are many real time simulators such as RTDS, HYPERSIM and ARENE [11-14]. These simulators are capable of testing real time power network simulations with real life networks or simulation that operates in real time like QualNet [10]. Real time simulator has the capability to run complex models at the same time as the physical time. There are tremendous advantages of using real time simulators in terms of development time and lower costs when they are integrated with the HIL and SITL simulations. For example it will advantageous to use HIL simulations under different conditions and scenarios, such as for normal and transient situations otherwise it would be costly or difficult to test with a physical plant. Real time simulation is not the goal of our research however the focus is to integrate the power and network communication so that simulation time clocks of both advance seamlessly.

It is assumed that all subsystems are synchronized together with very high precision allowing multiple controls under test to be connected to the system simultaneously. There are four main objectives for modelling and simulation of energy management system:

- Design of control algorithms for energy management and their corresponding software architectures.
- Analyse the requirements of and impact of communication technologies on the performance of control algorithms.
- Better design of the controller.
- Development of flexible and modular simulation environment.

These requirements are important for investigating in the context of energy management system for the development of smart charging algorithms that
can reduce peak power; minimize the energy costs and optimal use of renewable energy sources.

4.1.1 Communication effects in control system

Electric vehicles may be considered as dynamic load requiring large amount of power from the grid but also capable of feeding power from the vehicle to grid (regeneration). Properly designed and controlled network can provide ancillary services and supply the supply network, such as frequency regulation by controlling the active power flow, supply/demand matching and the reactive power support. Communication thus plays an important role in managing the distribution of energy. It is important for the charging station about the state of the grid in order to better estimate the times for charging [24]. Different communication methods can be adopted for charging stations such as Power Line Carriers (PLC), IEEE 802.15.4 (Zigbee) etc. [25].

Integration of communication and power systems/power electronics can be considered as Networked Control System (NCS) in which there is a communication between the remote controller and plant. It is important to mention here that there are several communication factors which affect the performance of NCS like, latency, packet losses, and bandwidth and packet size including packet disordering. Hence NCS can be considered as stable when the effects of the network are not taken into account but unstable in real life conditions.

4.1.2 Nature of delays

In [26] it is shown that delay can be decomposed into two parts as shown in Figure 3: Controller to actuator \( \tau_{ca} \) and sensor to actuator \( \tau_{sc} \). In order to model the system correctly it is important to classify the nature of delays like, random, time varying, or constant and bounded or unbounded, depending on the Medium Access Control (MAC) protocol [27].

There are varieties of medium access protocol for wired and wireless networks including Carrier Sense Multiple Access (CSMA), Time Division Multiple Access (TDMA), Token Bus, Token Ring and Token Passing. Where, a CSMA protocol offers uncertain or random delays e.g. Controller Area Network (CAN) or Ethernet while TDMA or Token type’s offers deterministic type of latency.

4.1.3 NCS modelling

There are different types of control methods for modelling NCS, in which some methods require history of the delays. Stochastic methods are employed for random type of latency like Poisson and Markov [28]. [29] has adopted discrete approach for the deterministic delays in the NCS:

\[
\dot{x}(\tau + h) = \phi x(kh) + \Gamma_1 (\tau) u(kh) + \Gamma_0 (\tau) u[(k - 1)h] 
\]

(16)

Where, \( h \) is the sampling period and

\[
\tau_k = \tau_{ca} + \tau_{sc}
\]

\[
\phi = e^{Ah}
\]

\[
\Gamma_0 = \int_0^{\tau} e^{At} Bds
\]

\[
\Gamma_1 = \int_{\tau}^{h} e^{At} Bds
\]

Furthermore the system can be represented in the form;

\[
\tilde{x}(k + 1) = \tilde{A} \tilde{x}(k) + \tilde{B} \tilde{u}(k)
\]

(17)

Where,

\[
\tilde{A} = \begin{bmatrix} \phi & \Gamma_1 \\ 0 & 0 \end{bmatrix}, \quad \tilde{B} = \begin{bmatrix} \Gamma_0 \\ 1 \end{bmatrix}, \quad \tilde{x}(k) = \begin{bmatrix} x(k) \\ u(k-1) \end{bmatrix}
\]

If the periodic delay \( \tau \) is less than the sampling period, the system will still be considered time invariant and the stability of the system can be calculated by a regulator such as;

\[
\tilde{u}(k) = -K \tilde{x}(k),
\]

by computing the eigenvalues of the matrix \( \tilde{A} - \tilde{B}K \).

This method will be adopted for future studies in smart grid and EV applications. With the platform discussed in Section 2 it is possible to simulate the model developed.
5 Case study

In this section, a case study of a modern distributed system is presented. The purposes of this model are to test the effects of distributed generators that create reverse power flow in the distribution network and bi-directional power flow which affect the quality of power supply and voltage levels. There are increased fault current due to the distributed generations, malfunctioning of protection system and phase imbalance.

Electric vehicles are considered as active loads. They may affect the transient voltage stability of the distributed network both in charging and discharging (regeneration) mode of operation. The impact is expected to be significant due the increasing penetration of EV and increase in use of induction motor load. The resultant effects are analysed for the design of better EV interface devices and future power networks. It is possible to design the EV interface to eliminate the effects of EV on the network fault level and the protection system. However, their effects on the network such as loading, voltage profile, and phase imbalance and power quality could be significant and need to be properly addressed.

5.1 Model Description

Consider radial network shown in Figure 1. Each feeder contains different portions of static load in parallel to the induction motor load such as, Feeder A contains residential subscriber loads containing ordinary loads (about 50% induction motor load), static loads and charging pile for charging of electric vehicles, while feeder B, feeder C, and feeder D are commercial building subscriber loads which contain less-sensitive loads (about 65% induction motor load) and static load, ordinary loads (about 50% induction motor load) and static loads, and sensitive loads (about 75% induction motor load) and static loads, respectively. The charging station deployed at feeder D is considered to provide transient voltage stability for this research. The battery SOC can be reached by 80%-90% within 30 minutes. EVs are normally in constant current charging and its active power is far more than the constant voltage charging. For this research the charge current and discharge current is of worth importance. As given in Table 2 the routine charging for our case has DC bus voltage of 380V, the charging current is 63A, and the active power is 24kW.

The distribution network has two modes of operation grid connected and islanded. During grid connected mode the battery storage inverter is delegated to keep the dc voltage stable and goal of the dc-dc converter is to control the current level of the battery both in either charging or discharging mode. While during islanding mode the battery storage inverter will change its mode to keep constant grid voltage and the converter will maintain the DC bus voltage by changing its mode to voltage control mode.

When there is three phase fault happens at the grid, a signal is sent to the microgrid ESMS to synchronize the load. If there is voltage instability indicated by any bus the charging station is requested for the reactive power support. The measurements sent through the communication link contain latency, bandwidth limitation and packet losses as introduced. As the electric vehicles are added to the system or by the increase in motor load a drop on the ac bus voltage signifies that static as well as dynamic load has to be served.

In our simulation first we considered the impact of increasing EV load (charging mode of EVs). Later we considered the impact of increasing penetration of EV (discharging mode of EVs) in order to conform the transient voltage stability margin index explained in section 2.5.1.

5.2 Model distribution

The distributed network model is mainly distributed into power system and communication system interfaces. DiGSilent Powerfactory and OPNET can be used for the simulation of continuous time and discrete event system simulations.

5.3 Simulation Analysis and Results

Considering that the demand of charging the electric vehicle reaches maximum and the Feeder D has bigger proportion of induction motor, it is expected that this feeder can lose the stability within no time on a 3 phase fault at the power grid. It is noteworthy that increasing load of EV as it reaches about 40% the system will become unstable i.e. with the increasing penetration of EV load the transient voltage stability margin becomes lower due to decrease in the node voltage as shown by Figure 4.

The charging station merely supports completely in this situation and the system will be going to be unstable in this situation. In order to improve the transient voltage stability margin index the electric
vehicles penetration may be increased in V2G mode. By increasing the penetration in V2G mode the transient voltage margin index follows the EV discharging in an event of fault and the state of distribution network will transfer from and unstable state to the stable state. The impact of electric vehicle penetration to maintain the voltage stability of the node is shown in Figure 5. Hence, it is proposed that configuration of electric vehicles has to be changed from charging mode to discharging (V2G) mode. The critical clearing time as depicted by the transient voltage stability margin index is very much important and reconfiguration of electric vehicles must fast enough to maintain the transient voltage stability margin index.

In our study we considered separate transient voltage stability margin indices for static load, complex loads and the EV loads and found that with the increasing EV load the transient voltage stability margin index become lower, there is an indirect relationship between increase in EV load and the transient voltage stability margin index. Moreover there is direct relationship between EV penetration and the transient voltage stability margin index.

6 Conclusions and future works

This paper discusses about the impact of energy management of electric vehicles on transient voltage stability of microgrid. In the presence of fault of in the power grid, the microgrid is islanded. Energy management is necessary to balance the demand and supply. Electric vehicles can provide the base load for short term and can act as spinning reserve to enhance the grid stability. Transient voltage stability of the distribution network especially microgrid can be achieved through the penetration of electric vehicles. Furthermore, the use of induction motor load is also increasing and induction motor is a threat for grid stability either during start-up/disturbance. We are keen to normalize the transient behaviour of induction motor load through the electric vehicles. In this paper we have proposed a transient voltage stability margin index as measure of stability of the distribution network/microgrid. Moreover we proposed an energy management algorithm for the distributed vehicles in the microgrid for the purpose of load synchronization. The energy management algorithm and transient voltage stability margin index may be used in conjunction to limit the number vehicles in the network and managing configuration of the vehicles either as load or source. In order to fully exploit the idea the co-simulation of the energy management system may be implemented in future.

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References


Authors

Muhammad Shoaib Khalid has received Master’s degree from Hanyang University, South Korea in 2010. He is presently a PhD candidate in the School of Electrical and Electronics Engineering at Huazhong University of Science and Technology, China. His research interests include energy management of microgrids and power system optimization and control.

Xiangning Lin received a Master’s and PhD degree from School of Electrical and Electronics Engineering at Huazhong University of Science and Technology, China. His research interests are modern single processing and its applications in the power systems, power system protective relaying and control.

Yixin Zhuo is pursuing Master’s leading to PhD degree from School of Electrical and Electronics Engineering at Huazhong University of Science and Technology, China. His research interests are related to wind energy.

Ramesh Kumar has received Master’s degree from Hanyang University, South Korea in 2010. He is presently a PhD candidate in the School of Electronics and Computer Engineering at Hanyang University, South Korea. His research interests include protocol development of smart grids.

Muhammad Kashif Rafique received has received Master’s degree from UET Taxila, Pakistan in 2010. He is presently a PhD candidate in the School of Information and Communication Engineering at Sungkyunkwan University, South Korea. His research interests include charging optimization of electric vehicles.