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Impact of plug-in electric vehicles on voltage unbalance in distribution systems

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Abstract

Plug-in electric vehicle (PEV) will soon be connected to residential distribution networks. They are considered as huge residential loads when being charged. However, as the battery technology and required facilities improves, they will also be able to support the network as small dispersed generation units which transfer the energy stored in their battery into grid. Even though the PEV connection gradually increases, their connection points and charging/discharging levels randomly vary. Therefore, such single-phase bi-directional power flow can have adverse effect on the voltage unbalance of a three-phase distribution network. In this work, impact of plug-in electric vehicles on voltage imbalance in distribution system is presented. In G2V as well as V2G modes, the voltage unbalance analysis is carried out for various cases. Additionally, the voltage unbalance due to PEVs discharging and other types of distribution generator such as solar photovoltaic and wind turbines are investigated. Finally, some voltage unbalance mitigation techniques are summarized.

Keywords: Distribution Network, Electric Vehicle, G2V, V2G, Voltage Unbalance.

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1. Introduction

World is already started confronting with energy crisis and climate change. The world's future energy is at risk due to volatility in petroleum prices, security concerns associated with imported oil. Global warming refers to an explicit and continuing rise in average global temperatures. The most of global warming problems are caused by increasing in concentrations of greenhouse gases such as Carbon Dioxide (CO_2) produced by human activities. In other words, global warming also refers to the anthropogenic climate change. The transportation sector (Sandalow *et al*, 2009 and Short *et al*, 2009) is one of the major contributors of carbon dioxides, where the passenger vehicles account for half of the emissions from the sector. It is necessary for global to look for alternative vehicle technologies that are more efficient and emit less carbon dioxide than traditional. Electric Vehicles (EVs) are considered as one of the promising future technologies that increase energy security and reduce greenhouse gases emissions. Therefore, Electric Vehicles Initiative (EVI) policy forum was dedicated by multi-government to accelerating the introduction and adoption of electric vehicles worldwide.

Plug-in electric vehicle (PEV) (PEV, 2014) is electric vehicle that can be plugged into an electrical outlet or public charging station to recharge its battery, and the electricity stored on board drives or contributes to drive the wheels. In BLUE Map scenario (IEA, 2013; IEA, 2011; Nemry *et al*, 2009) the transport sector is set to reduce CO2 emissions levels to lower than 30% in 2050 comparing with 2005 levels. According to this scenario, IEA estimates that EV/PHEV sales share will replace convention vehicles and will increase to at least 50% of LDV sales worldwide. Since 2010, EVs and PHEVs have begun to penetrate the market. EVs are expected to reach 2.5 million vehicles sales per year by 2020 whilst PHEVs reach nearly 5 million sales by 2020. Sales of PHEVs and EVs are expected to achieve even greater levels of market share and begin declining after 2040. By 2050, 50 million in annual sales is the ultimate target to achieve for both types of vehicles.

This means that PEVs can operate as loads (G2V mode) (Letendre *et al*, 2006 and Li *et al*, 2009) or generators (V2G mode). Although the adoption level of PEVs gradually increases, the charging/discharging patterns of PEVs in residential distribution system depend on customer behavior which is uncontrollable. Therefore, PEVs as a large single-phase bi-directional power flow can have adverse effect on the voltage unbalance of a three-phase distribution network. For example, it could cause the voltage unbalance in the three-phase distribution system, and also leads to the unbalanced current flow in neutral wire. The neutral current has an effect on the system losses due to $P_{loss} = I_{neutral}^2 \times R$. Fundamentally, when the system losses increase, the heat will rapidly rise and damage equipment.

The study of the impacts of PEV battery charging rates, which comparing the different charging rate such as slow, medium and fast charging, PEV penetration levels, charging periods and existing load variations (Masoum *et al*, 2010) demonstrated that the medium and quick PEV charging at peak period might have significant impact on the transformer loading in high-voltage system (23 kV). This study also presented that PEV charging in the low-voltage system can cause distribution transformer to overburdened and considerably reduce loss of life. Voltage deviation, power losses, and peak demand in the smart grid are significantly affected by PEV charging period.

Typical EVs are provided with batteries having energy storage capacities from some kWh up to several tens of kWh (Li *et al*, 2012 and Brooks *et al*, 2002). Accounting losses, charging such batteries means even higher energy usage from distribution network. It has to be kept in mind that for providing acceptable convenience level for the EV owner the battery would require full recharge in time of just limited hours. To accomplish this, power of the chargers is expected to be high, starting from 1.6 kW for single phase onboard chargers for home use (Shao *et al*, 2011) reaching into hundreds of kW for ultrafast charging (Hõimoja *et al*, 2010). As the most probable location for EV charging is home (Zhao *et al*, 2010) the likelihood of addition of powerful single-phase loads to the residential network is very high.

The increasing use of EVs is being promoted actively for several benefits in environmental aspects and energy efficiency. Assuming thermal power plant origin of power, overall EV efficiency is at least 23.1% (Roe *et al*, 2009) while a vehicle with internal combustion engine utilizes 12.5% of fuel primary energy. Discussions in public are however not regarding the effects to electrical networks and it is often presumed that the distribution networks provide the necessary overhead and are ready to accept the EV charging loads (Green *et al*, 2010) The distribution network transfer capacity availability has recently seen quite much discussion, with results presenting clearly that the distribution networks can have limitations in EV charging (Richardson *et al*, 2010). Reference (Tikka *et al*, 2011) supports even for a relatively low EV penetration levels. As a remedy, several control and moreover smart charging scenarios have been proposed to increase the charging capabilities to the network (Golbuff *et al*, 2007 and Trovao *et al*, 2011).

Topics for the analysis of EV charging impacts to distribution networks can be listed as thermal loading, voltage regulation, harmonic distortion levels, unbalances, losses and transformers loss of life (Taylor *et al*, 2009). Masoum *et al*, (2010) demonstrated that the medium and quick PEV charging at peak period might have significant impact on the transformer loading in high-voltage system (23 kV). Pieltain *et al*, (2011) studies the impact of plug-in electric vehicles on distribution network by using a planning model for large-scale distribution network. Putrus *et al*, (2009) presented the current and result of voltage unbalance that had been experimented for a car park and relatively high power transformer (1 MVA) was employed only for the supply of 140 units EV single-phase chargers with rated current of 10 A Comparing to standards for compatibility levels of 2% in LV networks (IEC, 2002) there is still some headroom, though not very much. Shahnia *et al*, (2011) conducted voltage unbalance analysis using the voltage unbalance sensitivity definition in terms of a function of EV charging location in the grid and the charging current.

Another stochastic model was applied by (Qian *et al*, 2010) for estimation of load demand in UK distribution system resulting from EV charging. Some modeling aspects presented in (Collin *et al*, 2011) and seen impact in (Clement-Nyns *et al*, 2010).
To compare the results of EV charging in different scenarios like smart charging and uncoordinated charging, various studies have tried to implement the demand side management programs i.e. critical peak pricing, real time pricing or dynamic pricing, peak time rebate and time of use rate etc.

Once this problem of overloading transformer is resolved, there are more options to solve other issues like short transformer life and high costs of up-gradation (Shao *et al*, 2011).
Reference (Singh *et al*, 2010) studied the impacts of EV connection on power quality including voltage deviation and system losses in the Indian Grid by considering different EV penetration levels as well as different patterns of EV charging.
Reference (Chua *et al*, 2012) suggested the technique for the voltage unbalance mitigation due to high penetration level of PV by using energy storage system (ESS).

However, PEV could be the serious cause of voltage imbalance in three-phase distribution system. In near future, the adoption level of PEV is going to grow rapidly, it is important to investigate the impact of PEV on voltage imbalance in distribution system. Therefore, voltage unbalance analysis and the mitigation techniques are focused in this work.
This paper aims to summarize the investigation presented until now about the aspects of harmonics and load unbalance associated with EV charging. Therefore, the main objective of this work aims to investigate the impact of PEV on voltage imbalance in distribution system as well as to suggest and analyze the technique to mitigate the voltage unbalance. The specified objectives are as follows:

1. To investigate the voltage unbalance of PEVs charging in distribution system in G2V mode.

2. To investigate the voltage unbalance of PEVs discharging in distribution system in V2G mode.
3. To Suggest and analyze the techniques to mitigate the voltage unbalance.

2. Methodologies

2.1 Plug-in Electric Vehicle (PEV)

Electric vehicles are separated into three basic types that include (1) conventional hybrid electric vehicles (HEVs), (2) battery electric vehicles (BEVs) or all-electric vehicles, and (3) plug-in hybrid vehicles (PHEVs) or electric vehicle conversions of hybrid electric vehicles and conventional internal combustion engine vehicles. Ref. (Center for Sustainable Development, 2010) concluded "Although HEV have a battery, they can be only continuously recharged power from the internal combustion engine and regenerative braking and cannot be recharged from an external energy source. As a result, HEV do not belong to the category of plug-in electric vehicles". Therefore, the types of PEV are only BEV and PHEV.

2.1.1 Plug-in Hybrid Electric Vehicle (PHEV)

A plug-in hybrid electric vehicle (PHEV or PHV), also known as a plug-in hybrid, is a hybrid vehicle which include both an internal combustion engine and an electric motor. In other words, PHEV is simply an HEV with the additional ability to recharge its battery by plugging in a standard electrical outlet or charging station.

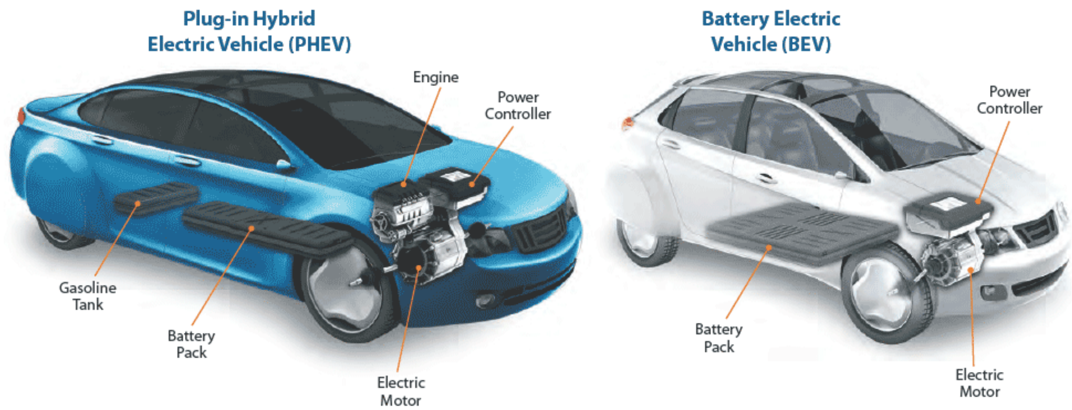

Figure 1. System technology of PEV

Depending on the model and driving conditions, PHEVs can travel about 15 to 50 miles after fully charged by using little or no gasoline. Once the battery is nearly depleted, PHEVs will switch to gas engine. The example is the Chevy Volt which has a battery range of 40 miles (mileage), which could be more than the average distance from home to work, without using gas.

2.1.2 Battery Electric Vehicle (BEV)

A battery electric vehicle (BEV) is a type of electric vehicle (EV) that relies solely on energy stored in rechargeable battery packs. BEVs use electric motors and motor controllers instead of internal combustion engines (ICEs) for propulsion. Today's BEVs can travel at least 60 to 160 miles on a full charge. For example: Nissan Leaf and Mitsubishi i-MiEV.

2.1.3 Plug-in Electric Vehicle Specifications

Table 1. Charging/discharging power rate and times with 220 voltages and 15 amperes level

	Nissan LEAF	GM Chevy Volt	Mitsubishi i-MiEV
Battery Capacity	24 kWh	16.5 kWh	16 kWh
When charging the Plug-in Electric Vehicle (G2V)			
Maximum charging rate	3.3 kW	3.3 kW	2.6 kW
Charging time (fully charge)	8 hours	5 hours	7 hours
When supplying power to the grid (V2G)			
Maximum discharging rate	3.3 kW	3.3 kW	1.5 kW
discharging time (fully discharge)	8 hours	5 hours	11 hours

In this study, Nissan LEAF, GM Chevy Volt and Mitsubishi i-MiEV, which have 24, 16.5 and 16 kWh of battery capacity respectively, are the major used models. According to IEC61851-1 (IEC, 2011) standard, Mode 1 specifies for slow charging from household socket that related to the EV connection to AC supply system using socket-outlets with the current that is not exceeding 16 A and the voltage that is not exceeding 250 V AC single-phase or 480 V AC three-phrase. Moreover, to extend battery life, the PEV users should avoid to fully charge or fully drained, therefore, the recommended range of battery capacity is to maintain between 30-70% of SOC (State-of-Charge). The summary information of EV connection are shown as Table 1.

2.2 Calculation of Voltage Unbalance

The three basic components of symmetrical three-phase voltages are the positive, negative and zero sequence voltage (Fortescue, 1918). The positive sequence voltage is also known as the "abc" and often denoted by the superscript "1" or "+". By the negative sequence voltage, the sequence of the phasors is the opposite direction from the positive sequence (acb instead of abc.) and often denoted by the superscript "2" or "-". Lastly, the zero sequence components of voltages are zero all in-phase sequence phasors and equal in magnitude and often denoted by the superscript "0".
According to (IEEE Standards, 1995) voltage unbalance occurs when the three phase voltages are unequal in magnitude and/or do not differ in phase angle by 120 degree. The voltage unbalance in three-phase network can be observed as a relation of negative sequence voltage to positive sequence voltage. The percentage of voltage unbalance is calculated as

$$VU\ (\%) = \left|\frac{V_2}{V_1}\right| \times 100 \qquad (1)$$

Where, V_1 and V_2 is the positive and negative sequences of the voltage, respectively.
Based on PEA Grid Code (PEA, 2009), the acceptable maximum voltage unbalance is limited to 2%.

2.3 PEVs Behavior Models for Charging and Discharging

The study of the voltage unbalance needs to establish the PEVs charging and discharging behavior models in order to define all of the possible situations. In general, the utility tries to balance the system by distributing equal loads in every phase, as well as residential loads. However, voltage unbalance problem possibly occurs when large and/or unequal single-phase load are connecting and disconnecting into the system at different interval time. After that, the PEV loads will charge equally in every phase and the voltage of system will balance. Therefore, in this study the voltage unbalance is analyzed only at the moment of PEVs are plugged-in and unplugged both of G2V and V2G mode as shown in Fig. 2. The start times of PEVs connection in phase A, B, C is t_1, t_2, t_3, respectively while the end times of PEVs connection in phase A, B, C is t_4, t_5, t_6, respectively. In addition, the interval time between each phase is 15 minute.

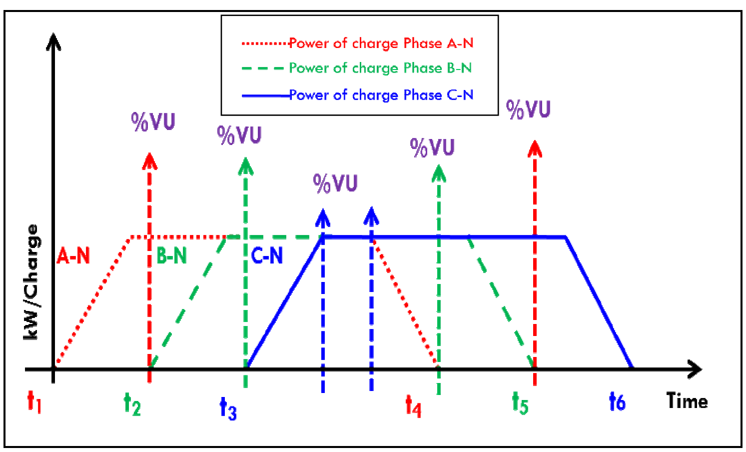

Fig. 2. Model of PEVs charging and discharging behavior on the distribution system

2.4 Suggested Methods to Reduce Voltage Unbalance

2.4.1 Time-of-Use rate (TOU)

Table 2. Electricity Prices in terms of Time of Use Rate (TOU)

Voltage Level	**Energy Charge** (Baht/kWh)		**Service Charge** (Baht/Month)
	Peak	**Off Peak**	
22-33 kV	4.5827	2.1495	312.24
less than 22 kV	5.2674	2.1827	38.22

Peak : Monday – Friday 09.00 AM – 10.00 PM
Off-Peak: Monday – Friday 10.00 PM – 09.00 AM
: Saturday–Sunday and all day of Official Holiday, excluding Substitution Holiday.

Time-of-use (TOU) (PEA. Home-Smart Grid, 2012 and PEA. The report of feasibility…, 2012) rate is a well-organized technique of demand side management (DSM) that encourages customers to avoid their electricity demand on peak period because of high price and shift the usage to off-peak period by setting the different price at different time period. DSM can be called as measurement to help electricity consumers for having cheap and efficient consumption. It also helps utilities to be more efficient hence reducing cost of system improvements.

In this investigation, PEA's TOU tariff rate is assumed to use for both buy (consume) and sell (generate) electricity from and to the grid. PEA provides TOU rate for residential service during 2011 to 2015 as presented in Table 2.

2.4.2 Energy Storage System (ESS)

Plug-in electric vehicle can work in two modes. First, it can work as load in Grid-to-Vehicle (G2V) mode that consumes electric power from the system. Second, it can work as distributed generator in Vehicle-to-Grid (V2G) mode that generates electric power return to the system. As a result, the demand of PEVs depends on customer behavior that cannot controllable. In this study, the capacity of energy storage system is assumed to be sufficient to deal with the voltage unbalance caused by the plug-in electric vehicles. The concept allows energy storage system to provide power to help balance loads by "valley filling" (charging when PEVs exceed generation) and "peak shaving" (sending power back to the PEVs when demand is high). The single-phase energy storage device is required to install in each house in order to mitigate the voltage unbalance. The single-phase energy storage system (ESS) is more suitable than the three-phase ESS because of lower cost, the ability to locate and connect in single-phase residential system. ESS will operate in peak period to mitigate the voltage unbalance in the system by storing electricity when PEVs exceed deliver electricity into the grid and providing stored electricity for PEVs when the demand is high. The single-phase energy storage device specification is assumed to same with Nissan Leaf battery and its capacity was large enough to cover all of PEVs demand.

3. System studies

Test system used is a practical distribution system, designated as Feeder-9, Nakhon Sawan-2 substation, of Provincial Electricity Authority (PEA) in Thailand. The test system has 14 nodes and load points. The network technical data is given in the Table A.1 in Appendix and its configuration is shown in Fig.3. The total loads (approx. 4,500 customers) in the system are 10.5 MW and 3.6 MVAr.

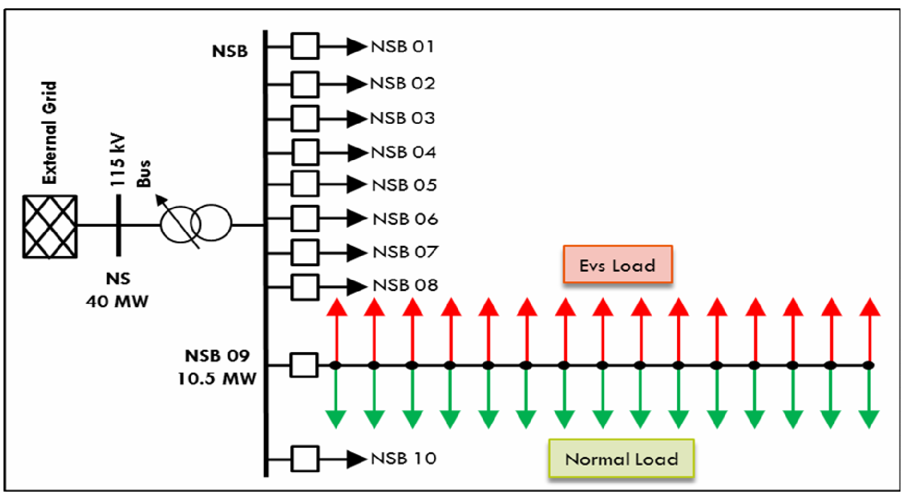

Figure 3. Configuration of the test system

The test system given in Fig. 3 is used to investigate the effects of PEV on distribution network. It is important to note that the three-phase voltage and current of system are balanced when no PEVs are connected. According to (Fortescue, 1918), the voltage unbalance is to be measured at 10 minute time intervals. The transient and intermittent characteristic of PEVs and loads are not focused in this study. Consequently, the PEVs are assumed as constant current load and generator in G2V and V2G mode, respectively.

Further, it has been assumed that the 100% PEV penetration level means every house has one PEV. Moreover, in this work, a deterministic approach in DigSILENT Power Factory licensed by PEA (PEA. Home-Smart Grid, 2012) has been used for analysis which has five various penetration levels, PEVs connected location, PEVs model that have different charging rate, and charging period as well as the impact of plug-in electric vehicles on voltage imbalance in distribution system.

3.1 Results and Discussions in G2V mode

In this study, there are five steps to conduct according to objectives.

First, define the PEVs load characteristic and the voltage unbalance in three phase distribution system. Second, define the load profile characteristic of residential distribution system. Third, define the load profile characteristic of residential distribution system. Next, investigate the voltage unbalance of PEVs charging in distribution system (G2V mode). For this scenario testing variables in this case, it includes the penetration levels, PEVs connected location, PEV model that have different battery capacity, and charging period. Table III shows the case studies for different scenarios in G2V mode.

Table 3. Scenario Test Variables when PEVs Charging in Distribution System (G2V Mode)

Scenario	Test variables	PEV Model	Location	Connected Period	Penetration Level (%)					
No.1	Penetration Level	Nissan Leaf	Uniformly Distributed	Peak	5	10	15	20	25	30
No.2	Location	Nissan Leaf	Beginning of feeder	Peak	5	10	15	20	25	30
			Middle of feeder		5	10	15	20	25	30
			End of feeder		5	10	15	20	25	30
No.3	Charging Period	Nissan Leaf	Uniformly Distributed	Peak	5	10	15	20	25	30
				Off-Peak	5	10	15	20	25	30
				During Day	5	10	15	20	25	30
No.4	Charging Level	Nissan Leaf	Uniformly Distributed	Peak	5	10	15	20	25	30
		GM Chevy Volt			5	10	15	20	25	30
		Mitsubishi i-MiEV			5	10	15	20	25	30

3.1.1 Results of variation in the PEVs penetration levels

For the first scenario, Nissan Leaf which is charged at 3.3 kW with 220V/15A home charger is used as a PEVs model. Furthermore, the household customers are 1,500 per phase. The charging time is peak load period. PEV penetration level of 5%, 10%, 15%, 20%, 25%, and 30% are considered reflecting 75, 150, 225, 300, 375 and 450 PEVs per phase. For example, 5% of PEV penetration level means 5% of 1,500 that equal 75 PEVs per phase. In this case, it is assumed the PEVs are equally distributed through the feeder.

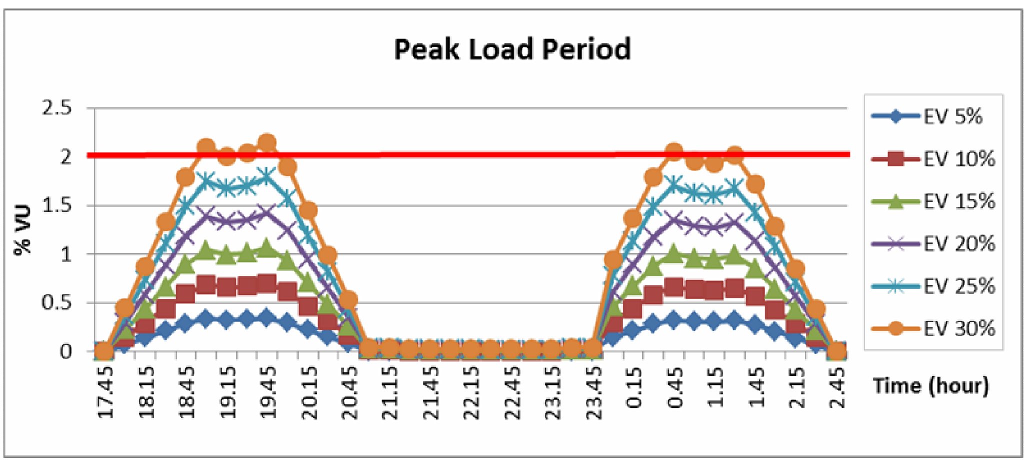

Figure 4. %VU vs. Time (h) with different PEVs penetration levels in G2V mode

In G2V mode, it is expected that the voltage unbalance will increase if penetration level increases. It can be observed that, the voltage unbalance is still within the PEA limit when adoption level of PEVs are 5%, 10%, 15%, 20% and 25% charged into the system .In the worst case, the connection of a PEV with 30% penetration levels caused voltage unbalance during 17.45 h to 21.00 h and 24.00 h to 2.45 h as shown in Fig 4. In addition, the maximum number of PEVs charging that the voltage unbalance does not exceed the 2% standard limit is 400 PEVs per phase or 26.67% penetration level of PEVs.

3.1.2 Results of variation in PEVs connected location

For the second scenario, there are three conditions which are used. First, a PEVs model is Nissan Leaf which is charged at 3.3 kW with 220V/15A home charger. Second, there are 1,500 household customers per phase. Third, the charging time is during peak load period. As a result, the consequences of this study investigate the voltage unbalance when altered PEVs connected location including the beginning, middle and end of the feeder at all penetration level.

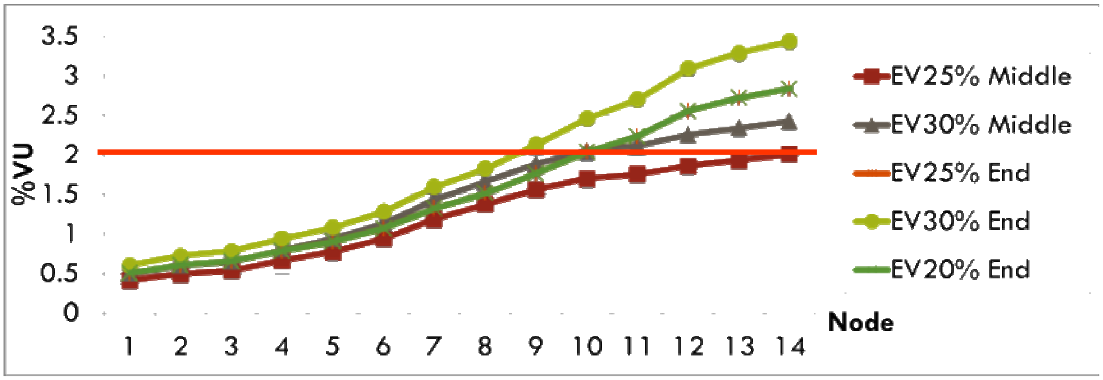

Figure 5. %VU vs. Time (h) with different PEVs connected location in G2V mode

As expected, the voltage unbalance increases when the PEV is connected to the far end nodes of the feeder and the impact is more when it is connected to the end of the feeder. From Fig 5, it can be seen that generally when the PEVs are connected to the end of the feeder, the %VU at the end points of the network is increasing when the PEVs are connected to the beginning or middle of the feeder. The voltage unbalance starts to over the limit when 25% PEVs charged at the middle of the feeder and 20% PEVs charged at the end of the feeder.

Moreover, the maximum number of PEVs, that the voltage unbalance does not exceed the 2% standard limit, are 350 PEVs per phase or 23.33% penetration level of PEVs when connected PEVs at the middle of the feeder, and 250 PEVs per phase or 16.67% penetration level of PEVs when connected PEVs at the end of the feeder. In contrast, the voltage unbalance is still within the limit at all penetration level when PEVs connects at the beginning of the feeder.

3.1.3 Results of variation in PEVs charging rate

For the third scenario, there are three conditions which are used. First, there are 1,500 household customers per phase. Second, the charging time is during peak load period. Third, PEVs were uniformly distributed through the feeder at 30% penetration level. According to Table 1, Nissan LEAF, GM Chevy Volt and Mitsubishi i-MiEV are the models to study to compare different PEV charging rates. Furthermore, the combination of all PEVs model are also studied and compared with each model. The ratio of PEVs combination is 50:35:15 (Nissan Leaf: GM Chevy Volt: Mitsubishi i-MiEV) according to global sales of the best-selling PEVs available for retail sales or leasing in September 2013.

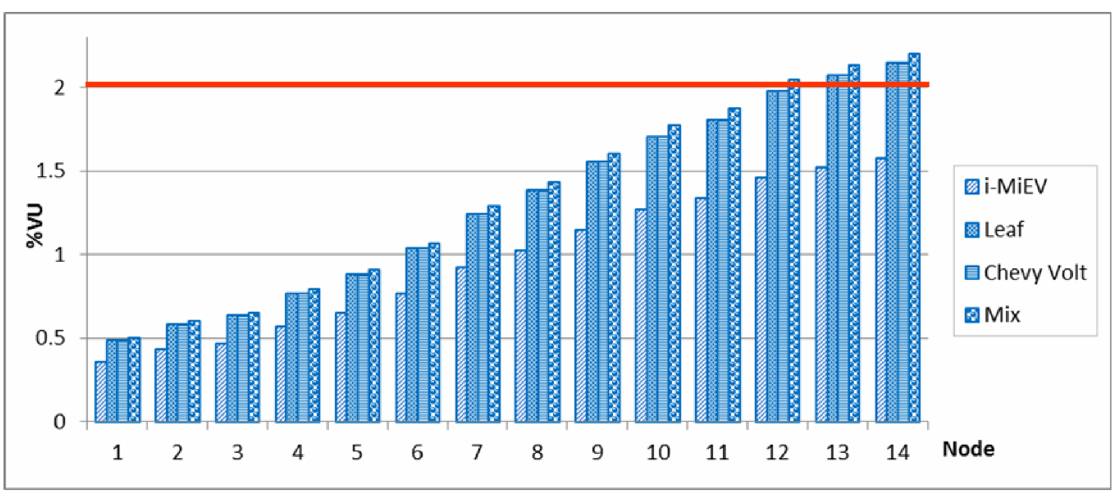

Figure 6. %VU vs. Time (h) with different PEVs charging rate in G2V mode

As Fig. 6 shows, the voltage difference between the phases increased if PEV has a higher charging rate. The voltage unbalance exceeds the 2% standard limit when connecting with Nissan leaf, GM Chevy Volt and the combination of all models. Because Nissan leaf and GM Chevy Volt have same battery capacity size that is larger than Mitsubishi i-MiEV, in addition, majority of combination ratio are Nissan leaf. The maximum of voltage unbalance percentage is 2.14 that occur at node-14.

3.1.4 Results of variation in PEVs charging period

For forth scenario, there are three conditions which are used. First, a PEVs model is Nissan Leaf which is charged at 3.3 kW with 220V/15A home charger. Second, there are 1,500 household customers per phase. Third, PEVs were uniformly distributed along the feeder at 30% penetration level. As a result, the consequence of this study investigates the voltage unbalance when alter PEVs charging period including the peak, off-peak and during day at all penetration level. As mention above, peak period is during 18.00PM to 24.00AM; off-peak period is during 24.00PM to 08.00AM and during day period is during 08.00AM to 18.00PM.

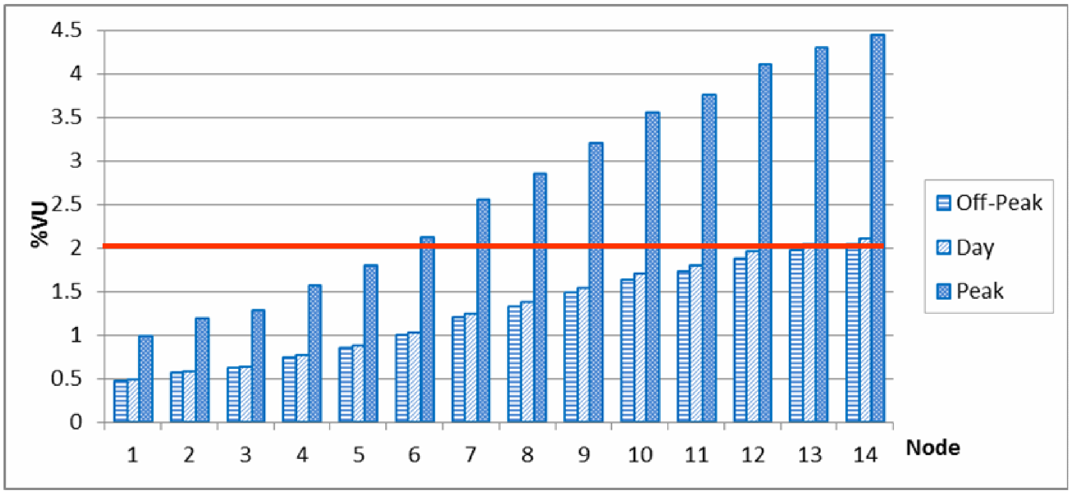

Figure 7. %VU vs. Time (h) with different PEVs charging period in G2V mode

As expected, the voltage unbalance increases if the loads demand are high. Figure 7 shows the connection of PEVs in peak load period resulting in the voltage unbalance dramatically increases and exceeds the 2% standard limit since node-6 onwards. The worst case occurred when PEVs connect to the system in peak load period at node-14 and the voltage unbalance is 4.446 %.

3.2 Results and Discussions in V2G mode

Then, investigate the voltage unbalance of PEVs discharging in distribution system (V2G mode). For the scenario testing variables in this case, it also includes the penetration levels, PEVs connected location, PEV model that have different battery capacity, and charging period. Table IV shows the case studies for different scenarios in V2G mode.

Table 4. Scenario Test Variables when PEVs Discharging in Distribution System (V2G Mode)

Scenario	**Test variables**	**PEV Model**	**Location**	**Connected Period**	**Penetration Level (%)**					
No.5	Penetration Level	Nissan Leaf	Uniformly Distributed	Peak	5	10	15	20	25	30
No.6	Location	Nissan Leaf	Beginning of feeder	Peak	5	10	15	20	25	30
			Middle of feeder		5	10	15	20	25	30
			End of feeder		5	10	15	20	25	30
No.7	Charging Period	Nissan Leaf	Uniformly Distributed	Peak	5	10	15	20	25	30
				Off-Peak	5	10	15	20	25	30
				During Day	5	10	15	20	25	30
No.8	Charging Level	Nissan Leaf	Uniformly Distributed	Peak	5	10	15	20	25	30
		GM Chevy Volt			5	10	15	20	25	30
		Mitsubishi i-MiEV			5	10	15	20	25	30
No.9	Type of DG	Nissan Leaf	Uniformly Distributed	Peak, During Day	5	10	15	20	25	30
		Photovoltanics	Uniformly Distributed	Peak	5	10	15	20	25	30
		Wind turbine	Uniformly Distributed	During Day	5	10	15	20	25	30

However, when PEVs are discharging to the system, they are working as one type of distributed generation (DG). Therefore, photovoltaic and wind turbine which are others types of DG will be compared with PEVs at same power discharging rate and different working time period.

3.2.1 Results of variation in the PEVs penetration levels

For the first scenario, Nissan Leaf which is discharged at 3.3 kW with 220V/15A home charger was used as a PEVs model. Furthermore, the household customers are 1,500 per phase. The discharging time is peak load period. PEV penetration level of 5%, 10%, 15%, 20%, 25%, and 30% were considered reflecting 75, 150, 225, 300, 375 and 450 PEVs per phase. In this case, it was assumed the PEVs are equally distributed along the feeder.

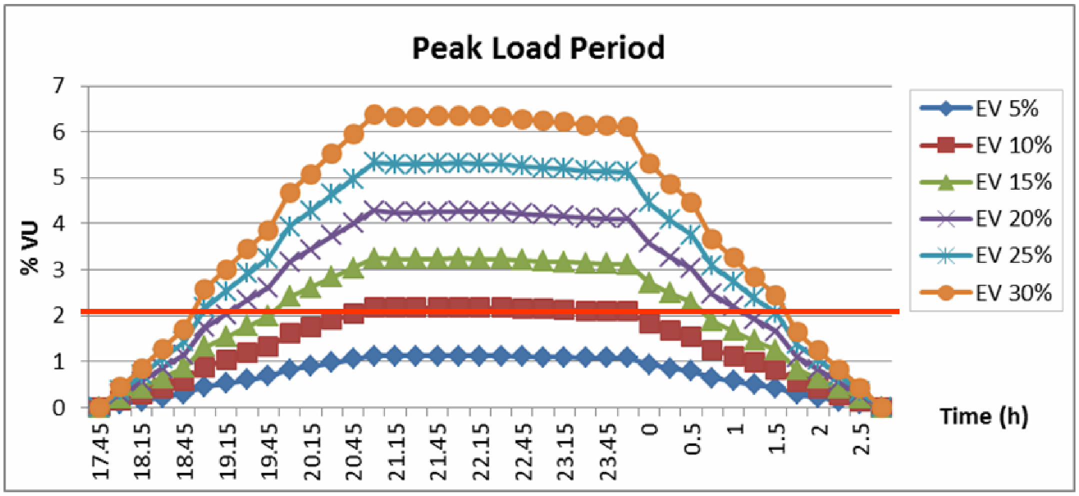

Figure 8. %VU vs. Time (h) with different PEVs penetration levels in V2G mode

In V2G mode, it is expected that the voltage unbalance will increase if penetration level increase. These results prove that, the voltage unbalance is still within the standard limit when adoption level of PEVs is 5% discharged into the system. However, the connection of a PEV with 10%, 15%, 20%, 25% and 30% penetration levels cause voltage unbalance during 21.00 h to 24.00 h as shown in Fig. 8. The maximum of voltage unbalance percentage is 6.350 that occurred at node-14. In addition, the maximum number of PEVs discharging that the voltage unbalance does not exceed the 2% standard limit is 130 PEVs per phase or 8.67% penetration level of PEVs.

3.2.2 Results of variation in PEVs connected location

For the second scenario, there are three conditions which are used. First, a PEVs model is Nissan Leaf which is discharged at 3.3 kW with 220V/15A home charger.

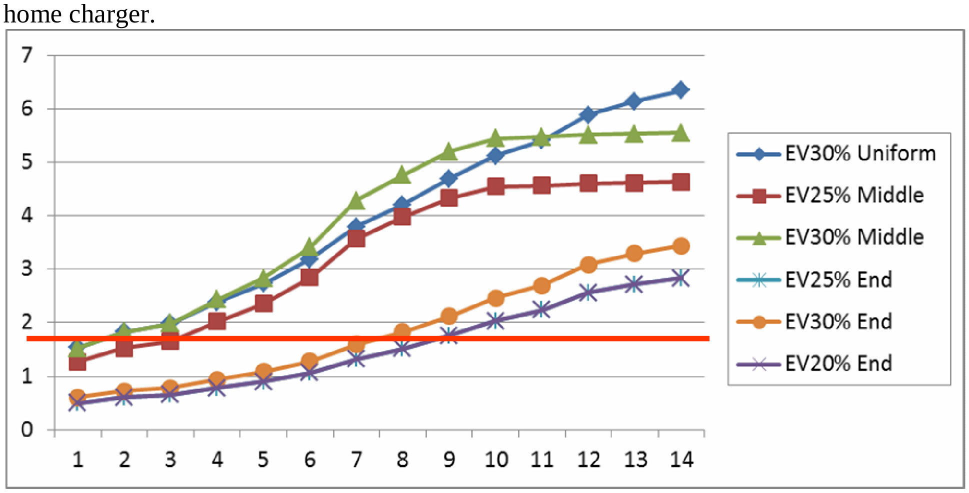

Figure 9. %VU vs. Time (h) with PEVs connected location in V2G mode

Second, there are 1,500 household customers per phase. Third, the discharging time is during peak load period. As a result, the consequences of this study investigates the voltage unbalance when alter PEVs discharging location including the beginning of the feeder, the middle of the feeder and the end of the feeder at all penetration level.

As expected, the voltage unbalance increase when the PEV is connected to the far end nodes of the feeder and the impact is more when it is connected to the end of the feeder. As Fig. 9 shows, it can be seen that generally when the PEVs are connected to the end of the feeder, the %VU at the end points of the network is higher when the PEVs are connected to the beginning or middle of the feeder.

However, the maximum of PEVs penetration level is limited to 15% due to contingency in the system. In addition, the maximum numbers of PEVs that the voltage unbalance does not exceed the 2% standard limit are 150, 150 and 45 PEVs per phase when connecting PEVs at the beginning, middle, and end of the feeder, respectively. Otherwise, the maximum penetration of PEVs is limited to 10%, 10% and 3% when connecting PEVs at the beginning, middle, and end of the feeder, respectively.

3.2.3 Results of variation in PEVs discharging rate

For the third scenario, there are three conditions which are used. First, there are 1,500 household customers per phase. Second, the discharging time is during peak load period. Third, PEVs were uniformly distributed along the feeder at 30% penetration level. According to Table I, Nissan LEAF, GM Chevy Volt and Mitsubishi i-MiEV which have battery capacity are 24, 16.5 and 16 kWh respectively are the studied model in order to compare different PEV discharging rates. Furthermore, the combination of all PEVs model was also studied and compared with each model. The ratio of PEVs combination is 50:35:15.

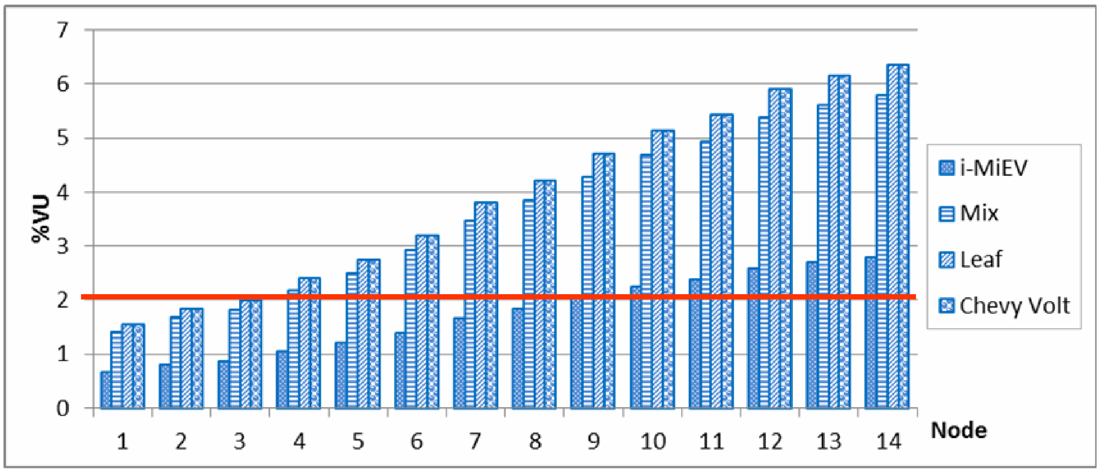

Figure 10. %VU vs. Time (h) with different PEVs charging rate in V2G mode

As expected, the voltage difference between the phases increased if PEVs has a higher discharging level. The voltage unbalance exceeds the 2% standard limit for all of models connection since node-9 onward. As shown in Fig. 10, the maximum of voltage unbalance percentage is 6.350 at node-14, when discharging by Nissan leaf and GM Chevy Volt as shown in Fig. 10.

3.2.4 Results of variation in PEVs discharging period

For forth scenario, there are three conditions which are used. First, a PEVs model is Nissan Leaf which is charged at 3.3 kW with 220V/15A home charger. Second, there are 1,500 household customers per phase. Third, PEVs were uniformly distributed along the feeder at 30% penetration level. As a result, the consequences of this study investigates the voltage unbalance when altered PEVs discharging period including the peak, off-peak and during day at all penetration level.

Figure 11 shown, the voltage unbalance dramatic increased and exceeded the 2% standard limit since node-3 onwards in every discharging period including peak load, off-peak and during day period. The worst case occurred when PEVs discharged to the system in peak load period and %VU is 6.350 at node-14.

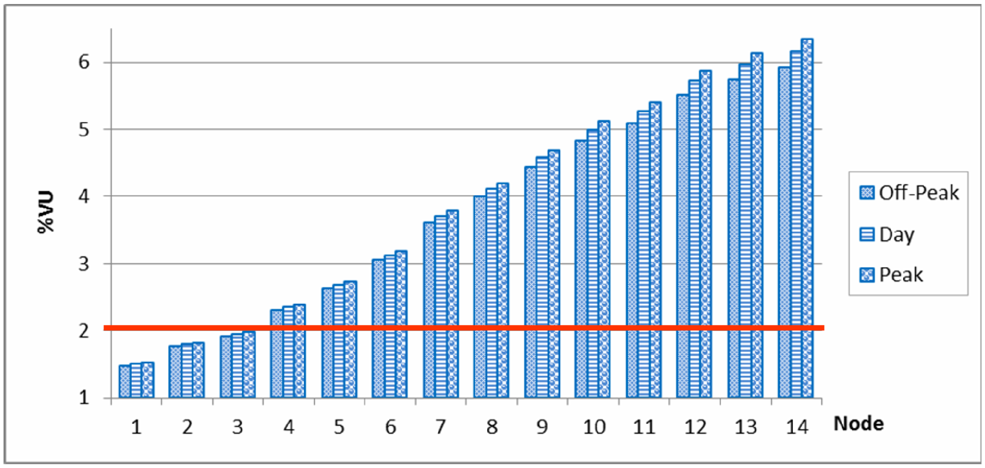

Figure 11. %VU vs. Time (h) with different PEVs discharging period in V2G mode

3.3 Comparison of voltage unbalance due to PEVs discharging and other types of DG

In the previous studies, results of PEV discharging variation are analyzed.

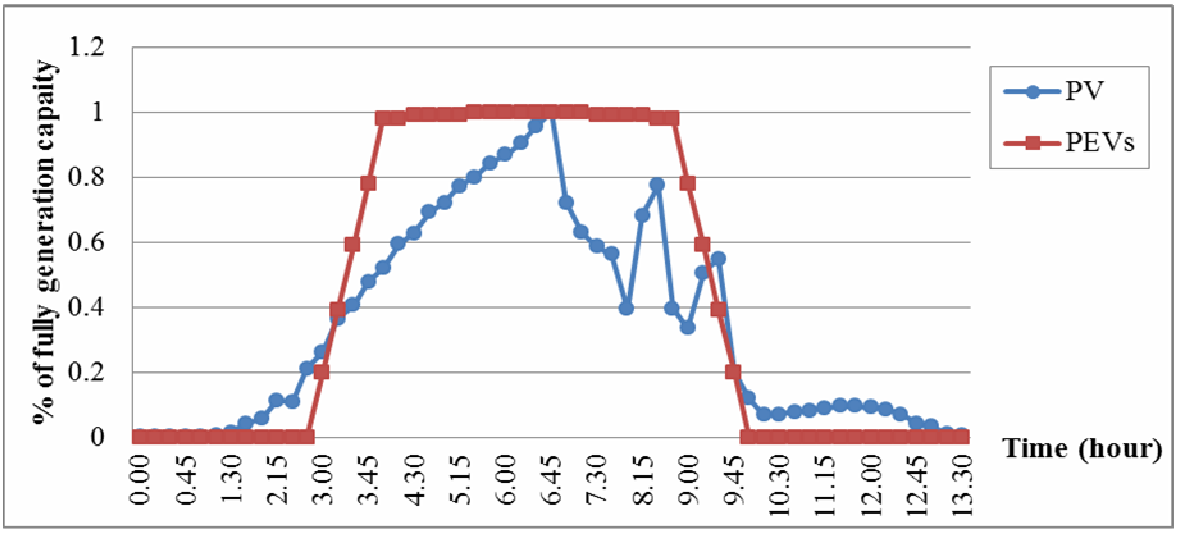

Figure 12. PV and PEVs daily generation shape comparison

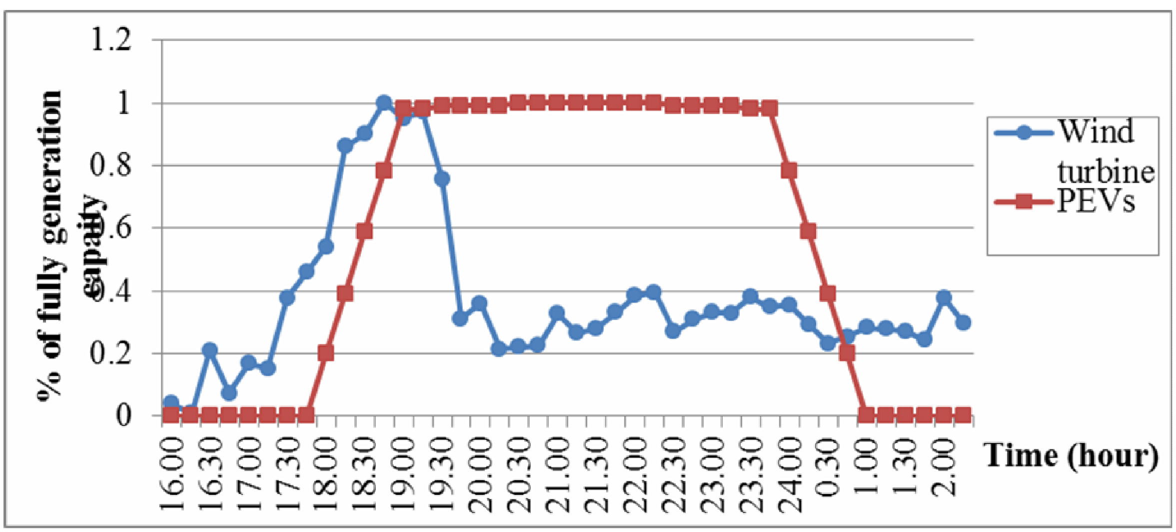

Figure 13. Wind turbine and PEVs daily generation shape comparison

As result of, PEVs when discharging to the system, it is working as a one type of distributed generation (DG). It is high interest to investigate the voltage unbalance that caused by PEVs and other types of DG discharging into the system. Therefore, the single-phase photovoltaic (PV) and wind turbines, which are others types of DG, are carried out to investigate this phenomenon.
The comparison daily generation shape from PV and PEVs is shown in Fig. 12 while wind turbine and PEV is shown in Fig. 13.

3.3.1 Comparison between solar PV and PEV

Figure 14 shown, the voltage unbalance comparison between PV and PEVs that can observe %VU of each DG is strongly depends on its power generation characteristics. Both of PV and PEVs caused the voltage unbalance exceeded the 2% standard limit during 8.00AM to 16.00PM. However, the generation output of PV systems fluctuates depending on solar radiation and weather conditions. As this result, the voltage unbalance that caused by PV was fluctuated more than PEVs. The worst case of PV discharging occurred during 11. 15AM and %VU is 5.780. In worst case of PEVs discharging occurred during 13.15PM and %VU is 6.246.

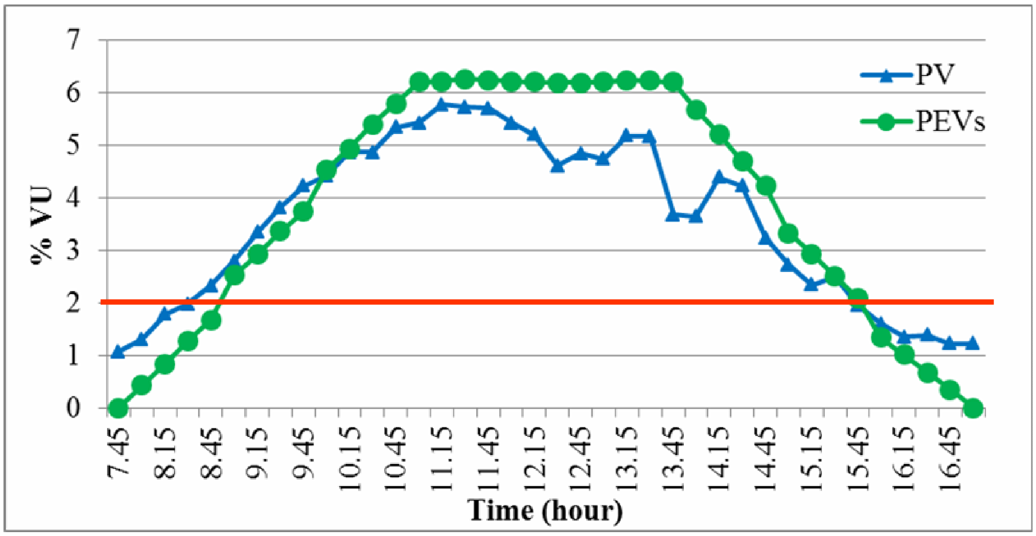

Figure 14. Voltage unbalance comparison between PV and PEVs

3.3.2 Comparison between Wind turbine and PEV

Figure 15 shows the voltage unbalance comparison between wind turbine and PEVs that can observe %VU of each DG is strongly depends on its power generation characteristics. However, the generation output of wind turbine systems fluctuates depending on wind speed.

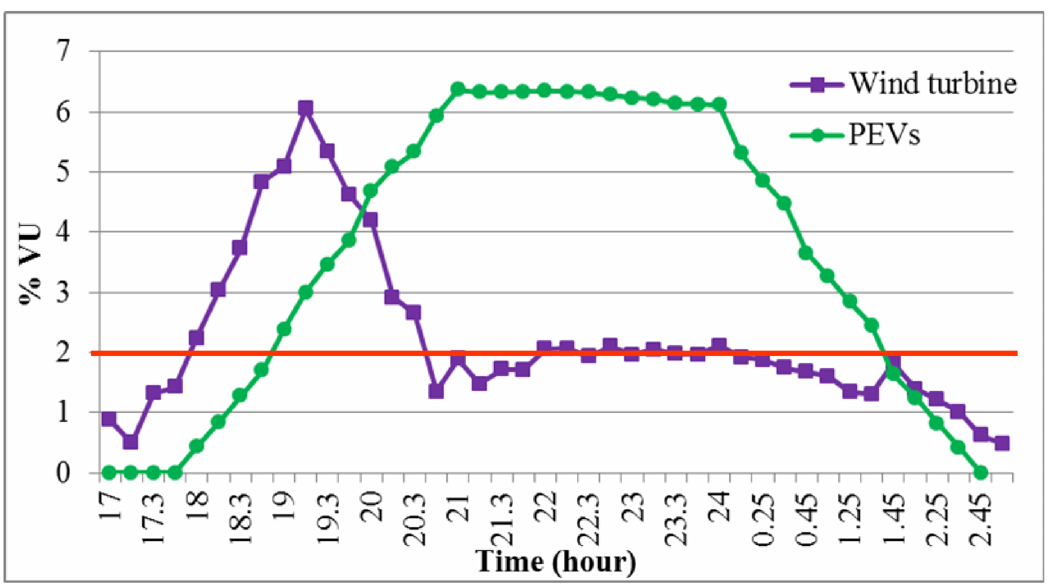

Figure 15. Voltage unbalance comparison between Wind turbine and PEVs

As this result, the voltage unbalance that caused by wind turbine was fluctuated more than PEVs. PEVs caused the voltage unbalance exceeded the 2% standard limit during 18.00PM to 2.45AM. In worst case of PEVs discharging occurred during 13.15PM and %VU is 6.365. Wind turbine caused the voltage unbalance exceeded the 2% standard limit during 18.00PM to 20.45PM and fluctuate between 1.5% and 2% during 20.45PM to 2.00AM. The worst case of wind turbine discharging occurred during 19. 15PM and %VU is 6.052.

3.4 Mitigation of Unbalanced Voltage

3.4.1 TOU tariff rate technique

- *The result of load shift due to TOU rate*

According to results of PEVs charging period variation in G2V mode, it is found that the voltage unbalance increases if the loads demand are high. Therefore, TOU tariff rate technique is carried out to mitigate the voltage unbalance.

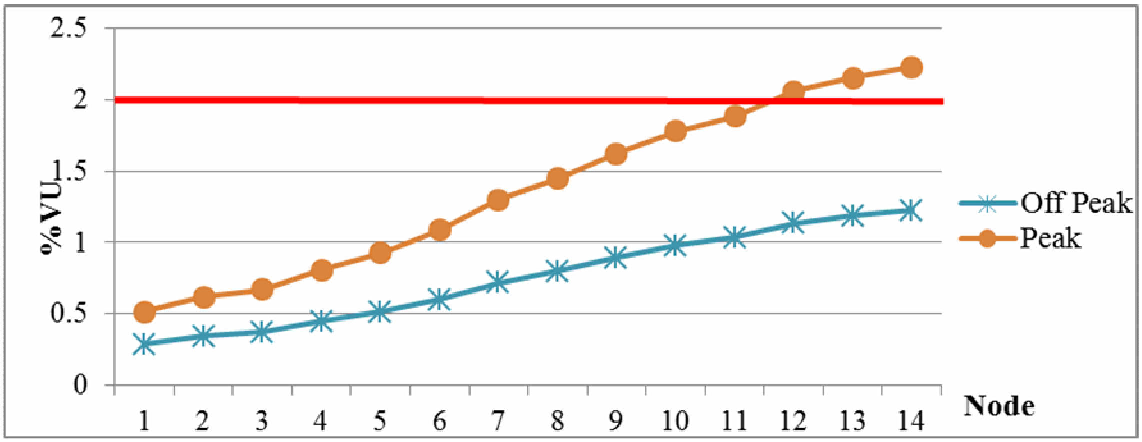

Figure 16. Voltage unbalance mitigation by load shift due to TOU rate

Figure 16 shown, the voltage unbalance dramatic increased and exceeded the 2% standard limit since node 3 onwards when charging in peak load period of TOU. When PEVs charged in peak period, the maximum of voltage unbalance was 2.227% in node 14. In contrast, the voltage unbalance was still within the limit when charging in off-peak load period of TOU.

- *The result of generation shift due to TOU rate*

According to results of PEVs discharging period variation in V2G mode, it is found that the voltage unbalance increases if the loads demand are high. Therefore, TOU tariff rate technique is carried out to mitigate the voltage unbalance.

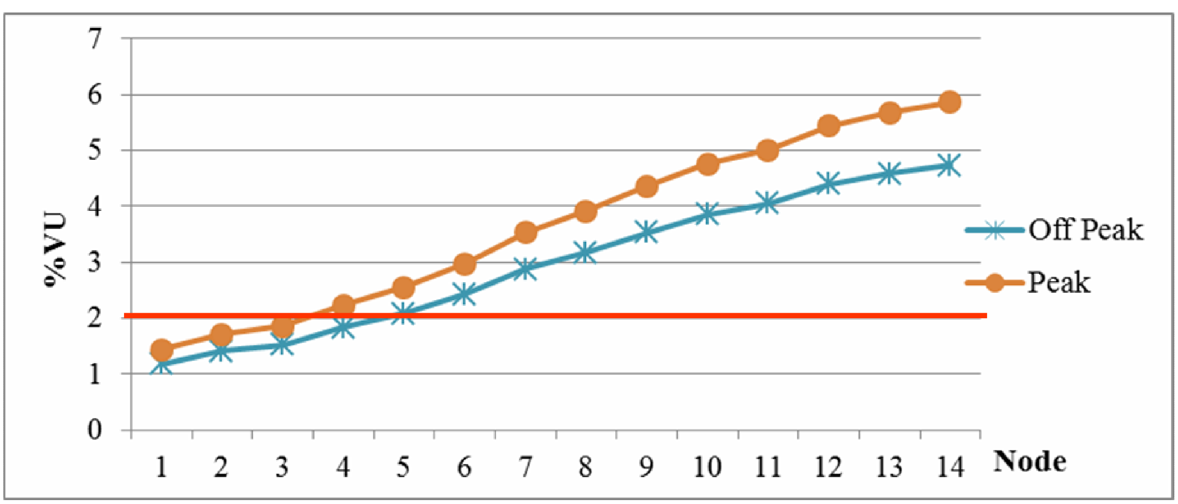

Figure 17. Voltage unbalance mitigation by generation shift due to TOU rate

Figure 17 shows the voltage unbalance dramatic increased and exceeded the 2% standard limit both of discharging in peak load and off-peak period. When PEVs discharged in peak period, the maximum of voltage unbalance was 5.867% in node 14. Meanwhile, the maximum of voltage unbalance was 4.732% when PEVs discharged in off-peak period.

3.4.2 Energy storage system (ESS) installation technique

- *The result of storage electricity for PEVs demand in peak period*

ESS is controlled to operate in peak period to mitigate the voltage unbalance in the system by provides stored electricity for PEVs when the demand is high. For this scenario, there are four conditions which are used. First, a PEVs model is Nissan Leaf which is charged at 3.3 kW with 220V/15A home charger. Second, the energy storage system is the single-phase energy storage device installed at each house and it is assumed to have discharging rate at 3.3 kW with 220V/15A and its capacity was large enough to cover all of PEVs demand. Third, there are 1,500 household customers per phase and uniformly distributed along the feeder. Forth, the studied time is during peak load period.
Figure 18 shows the voltage unbalance dramatic increased and exceeded the 2% standard limit when PEVs charged in peak load before ESS installation. In the worst case, the maximum of voltage unbalance was 2.038% at node-14. In contrast, the voltage unbalance could still within the limit after ESS installation.

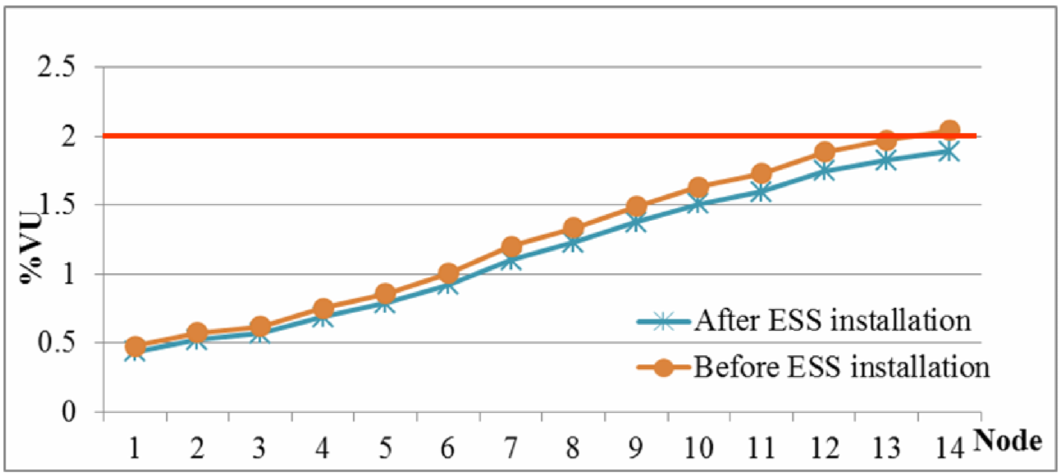

Figure 18. Voltage unbalance in G2V mode before and after ESS installation

- *The result of storage the exceed PEVs generation*

ESS is controlled to operate in peak period to mitigate the voltage unbalance in the system by stores electricity when PEVs exceed deliver electricity into the grid. First, a PEVs model is Nissan Leaf which is discharged at 3.3 kW with 220V/15A home charger. Second, the energy storage system is the single-phase energy storage device installed at each house and it is assumed to have charging rate at 3.3 kW with 220V/15A and its capacity was large enough to cover all of PEVs demand. Third, there are 1,500 household customers per phase and uniformly distributed along the feeder. Forth, the studied time is during peak load period.

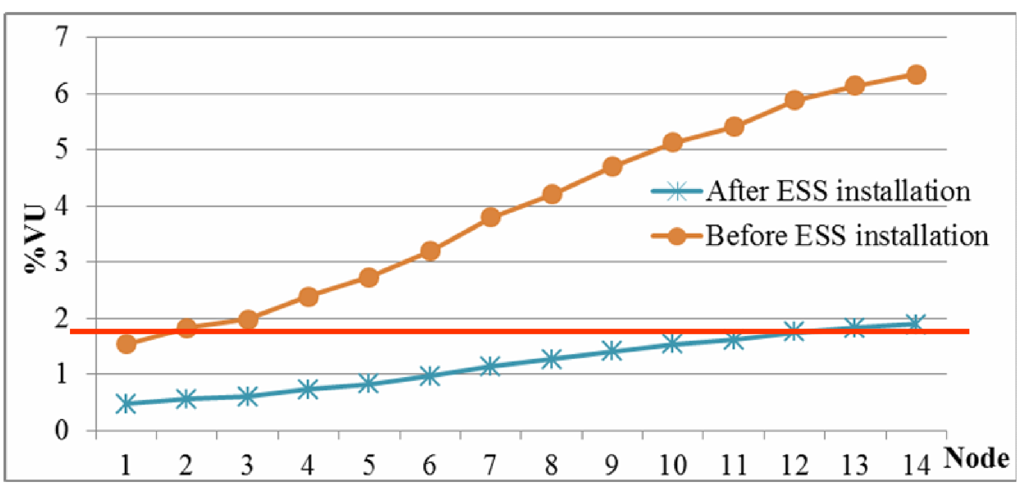

Figure 19. Voltage unbalance in V2G mode before and after ESS installation

Figure 19 shows the voltage unbalance dramatic increased and exceeded the 2% standard limit since node 3 onward when PEVs discharged in peak load before ESS installation. In the worst case, the maximum of voltage unbalance was 6.350% at node-14. In contrast, after ESS installation, the voltage unbalance could still within the limit and the maximum of voltage unbalance was only 1.885%.

4. Conclusions

The voltage imbalance on residential distribution system as a result of PEVs charging and discharging, as well as, the techniques of the voltage unbalance mitigation are presented in this paper. Through this studies, it is shown that the voltage imbalance will increase if penetration level of PEVs charging or discharging increases. It is also shown that PEVs will have greater impact on the voltage imbalance at the end of the feeder. Moreover, the results demonstrated the voltage difference between the phases increased if PEV has a higher charging rate. Furthermore, the voltage imbalance increases if PEVs charging or discharging when the loads demand are high. The comparison of voltage imbalance between PEVs and other types of DG shown that can observe %VU of each DG is strongly depends on its power generation characteristics. Finally, The voltage unbalance due to PEVs integrated into the system would mitigated by influencing the energy consumer to sign up for TOU tariff rate and install the single-phase energy storage device at each home.

To get further improved performances, a stochastic approach along with actual load profile, dynamic energy pricing (Time-of Use), and active compensation techniques (voltage source based converters) to mitigate the voltage unbalance could be carried out in the future study.

Nomenclature

EV	Electric Vehicle
EVI	Electric Vehicle Initiative
ESS	Energy Storage System
G2V	Grid to Vehicle
PEA	Provincial Electricity Authority
PEV	Plug-in Electric Vehicle
BEV	Battery Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IEA	International Energy Agency
LDV	Light-Duty Vehicle
DSM	Demand Side Management
TOU	Time-of-Use electricity rate
SOC	State of Charge
EPPO	Energy Policy and Planning Office
V2G	Vehicle to Grid
VU	Voltage Unbalance (%)

Appendix

Network parameter of given system in Fig. 3 is shown in Table A.1.

Table A.1: Technical Parameters of the Studied Distribution Network

Node	Load (MW)	Distance (km)	
		length	Cumulative length
1	0.00	0.00	0.00
2	0.40	1.00	1.00
3	0.70	0.50	1.50
4	0.50	1.40	2.90
5	0.80	1.20	4.10
6	1.00	1.70	5.80
7	0.50	2.50	8.30
8	0.60	1.80	10.10

Node	Load (MW)	Distance (km)	
		length	Cumulative length
9	1.20	2.30	12.40
10	0.50	2.50	14.90
11	0.60	1.80	16.70
12	0.70	3.50	20.20
13	0.80	2.30	22.50
14	1.50	2.50	25.00
15	0.70	2.50	27.50
Total	10.50	27.50	

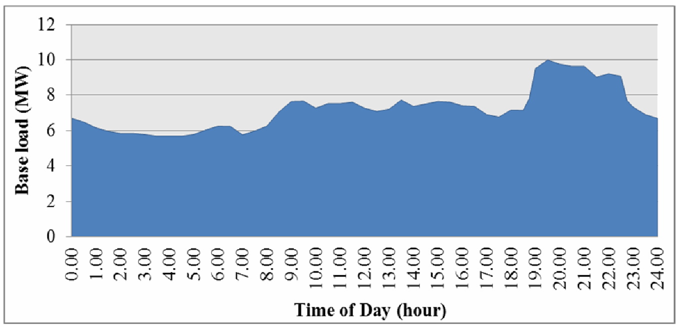

Figure A.1. Daily load profile of Feeder 9, Nakhon Sawan-2 substation

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