Voltage Unbalance Reduction in Low Voltage Feeders by Dynamic Switching of Residential Customers among Three Phases

Farhad Shahnia [1], Peter Wolfs [2] and Arindam Ghosh [3]

[1] Centre of Smart Grid and Sustainable Power Systems, Electrical and Computer Engineering Department, Curtin University, Perth, Australia.

[2] School of Engineering and Built Environment, University of Central Queensland, Rockhampton, Australia.

[3] School of Electrical Engineering and Computer Science, Queensland University of Technology, Brisbane, Australia.

[1] farhad.shahnia@curtin.edu.au, [2] p.wolfs@cqu.edu.au, [3] a.ghosh@qut.edu.au

***Abstract*—Low voltage distribution feeders with large numbers of single phase residential loads experience severe current unbalance that often causes voltage unbalance problems. The addition of intermittent generation and new loads in the form of roof top photovoltaic generation and electric vehicles makes these problems even more acute. In this paper, an intelligent dynamic residential load transfer scheme is proposed. Residential loads can be transferred from one phase to another phase to minimize the voltage unbalance along the feeder. Each house is supplied through a static transfer switch with three–phase input and single–phase output connection. The main controller, installed at the transformer will observe the power consumption in each load and determine which house(s) should be transferred from one phase to another in order to keep the voltage unbalance in the feeder at a minimum. The efficacy of the proposed load transfer scheme is verified through MATLAB and PSCAD/EMTDC simulations.**

***Index Terms*—Distribution Feeder, Load Transfer, Static Switch, Voltage Unbalance**

I. INTRODUCTON

Voltage Unbalance (VU) is one of the main power quality problems in distribution networks [1]. The unbalance is more common in Low Voltage (LV) feeders due to phase load inequality, especially where large single–phase loads are used. The network configuration and length has also impact on the VU in the feeder. In LV residential feeders, majority of the houses have single–phase power supply. The VU can be very high in these networks if the houses are distributed unequally among the three phases [2].VU is more likely to occur in LV networks with voltage drops close to the allowable limits,

The growing penetration of rooftop photovoltaic generators (PVs) in LV residential feeders has increased the VU problem in these networks. It can be expected that the number of rooftop PVs connected to each phase to be unequal. This will significantly affect the VU in the feeder depending on penetration level, rating and location of PVs along the feeder [3].

It is estimated that penetration of Plug–in Electric Vehicles (PEVs) into market will soon make the VU situation worse in LV feeders. In [4], it was shown that PEVs in both charging (Grid–to–Vehicle) and discharging (Vehicle–to–Grid) modes might lead to high VU in LV feeders.

The utilities aim to distribute the residential loads equally among the three phases of distribution feeders to minimize the VU in the network [2]. Currently, the electric utilities minimize the unbalance problem in LV feeders by manually changing the connection phase of some of the costumers. This is carried out by trial and error after monitoring the power and current unbalance in the secondary side of the distribution transformer for a limited time.

In [3], some conventional improvement methods such as feeder cross–section increase or capacitor installation are investigated for VU reduction in LV feeders. However, these methods are costly and may not be very efficient. In [5], the application of custom power devices such as Distribution Static Compensator (DSTATCOM) was proposed for VU reduction in LV feeders. It was shown that custom power devices can correct their Point of Common Coupling (PCC) to a balanced voltage. Hence, if the PCC voltage is balanced, the current drawn from the upstream network will be balanced and the unbalance will not penetrate to upstream. In [3], the utilization of rooftop PVs for exchanging reactive power was proposed for balancing their PCC voltage. Although this method is very efficient in unbalance reduction, however it might take a few years for rooftop PV connection standards to be adopted for this strategy.

In modern distribution networks, the sectionalizing switches and normally open tie switches are often used for reconfiguration of the network in Medium Voltage (MV) levels. In [6], it was proposed the network reconfiguration can be carried out by simply changing the phase connection of the three phases in the primary side of the distribution transformer for VU and power loss reduction. Therefore, based on the known load pattern for each distribution transformer, the optimum phase balancing was carried out. However, this practice is only carried out once and was not dynamic. In [7], it was shown that using Static Transfer Switches (STS), a sensitive load can be supplied from two different feeders. In this paper, the STS was used to prevent voltage sag/swell on a sensitive load by quickly transferring the input of the load from one three–phase feeder to another three–phase feeder. A similar network reconfiguration and Load Transfer (LT) scheme, derived from [6–7], can also be applied in LV feeders to re-

978-1-4799-1303-9/13/$31.00 ©2013 IEEE

duce VU in these networks. This is the main idea of this paper.

The electric utilities are converting the existing electric networks to smart grids by integrating devices with fast processing and bi–directional communication capabilities such as smart meters, controllers, automatic switches and power electronic based devices. So far, much research has been carried out on smart demand side management using these technologies where the controllers can manage the load consumption in the residential houses to prevent distribution transformers' overloading [8].

In such a network, the end–user controllers, installed at each house, will transmit the power consumption of each house to the main controller, installed at the distribution transformer, in 15–min time intervals. Once the main controller receives the power consumption of each house, it will analyse the network VU and total power consumption in each phase and will define which house(s) should be transferred from their current connected phase to another phase in order to keep the power mismatch between three phases and VU minimum all along the feeder. Once the desired houses are chosen, the main controller will send a signal to the chosen end–user controllers. Then, each end–user controller will activate the STS to change the phase connection for that house.

In this paper, an intelligent dynamic residential LT scheme is proposed as described above. A comprehensive analysis is carried out in MATLAB to investigate the VU and maximum and minimum of voltage along the feeder. The study later investigates the participation level of the houses in this scheme in addition to the effect of location of the houses along the feeder. Later, the performance of a power electronic based STS is investigated as the means of LT from one phase to another. Using PSCAD/EMTDC, the dynamic voltage and current characteristics of the load are investigated during the transition interval.

II. Voltage Unbalance Definition

Voltage unbalance in the three–phase electric system is a condition in which the three phase voltages (V_A, V_B and V_C) differ in amplitude and/or does not have its normal 120 degree phase difference. There have been several methods for calculation and interpretation of VU as investigated in [9–10]. In [10], it was stated that (5) is neglecting the zero sequence of voltage which cannot be neglected in LV feeders. That is because of the star connection of the loads and transformer in the LV feeders. Therefore, in LV 4–wire feeders, VU can be defined as

$$VU_{4-wire} = \frac{\sqrt{V_-^2 + V_0^2}}{|V_+|} \tag{6}$$

This will be referred to as percentage voltage imbalance in this paper.

III. Proposed Load Transfer Scheme

Fig. 1(a) shows the schematic of a typical radial distribution network in a suburban area. The MV feeder supplies several distribution transformers and each distribution transformer supplies several residential houses with single–phase supplies.

The main objective of the control system is to ensure VU is minimized all along the feeder while the power mismatch in three phases in the secondary side of the distribution transformer is also minimized. The preliminary stage of this scheme is that the utilities are aware of the phase connection of each house in the feeder. If this is not known, the method presented in [11] can be utilized in which the utilities can define the phase connection of a house by monitoring the power consumption and voltage in each house in a 7–day period.

A. Smart Meters

The dynamic concept of the LT scheme requires access to instantaneous power consumption by the residential loads. For this, all residential participants in the LT scheme should be equipped with smart meters [12]. The smart meters will transmit the power consumption of the house to the main controller in 15–min time intervals.

B. Controllers

In the proposed scheme, there will be two controllers. They are both microprocessor based and have two–way communication capability. The main controller will be installed at the distribution transformer. Each main controller is to only monitor and control the loads supplied form that transformer. The main controller will analyse the network VU and power mismatch between three phases after receiving the power consumption from smart meters in 15–min time intervals. Then, based on the proposed control method, it will choose the house(s) which a LT is required and subsequently will send a control command to the selected house(s).

An end–user controller will be installed at each LT scheme participant house. This controller will activate the STS once it receives a control command from the main controller.

C. Communication

Different communication methods have been already utilised in electric distribution and transmission networks such as Power line carriers, Optical fibre Ethernet, Internet, 3G/4G wireless, WiFi and ZigBee [13]. However, in recent years, ZigBee is the most preferred communication method for data transfer in smart grid applications in distribution networks. Therefore, in this paper, ZigBee–based communication for transferring the control commands from the main controllers to the end–user controllers is proposed. The available ZigBee devices along with their range extenders can easily cover an area of 1.6 km and have a data rate up to 250 kHz [13]. However, for this application, a very low–bandwidth is sufficient. Finally, the end–user controllers will send the confirmation of successful LT to the relevant transformer controller.

D. Static Transfer Switches

The proposed switching device is an AC Static Transfer Switch as shown in Fig. 1(b). The STS is composed of three switching devices, one for each phase. Each switching device is composed of anti–parallel thyristors or a Triac. Overvoltage protection and snubber circuits are in parallel with each switch [1]. Each switch is connected to one of the three phases of the system in input and their outputs are connected together and to the load. Only one switch at a time is operating; hence, the load with be connected to one phase while the other two switches devices are off. A logic interlock is implemented to block the operation of other two switches when the micro controller de–blocks one. This will prevent the short circuit between two phases in case the micro controller wants to connect two switches simultaneously due to a failure in the control/switching algorithm. The control command from the main controller identifies which switch should turn on. Once a control command is received from the main controller to the end–user controller, the conducting switch device will be blocked and the requested switching device will be de–blocked and the load supply will be continued.

It is to be noted that in the proposed STS, no auxiliary commutation circuit is utilised. Let us assume, that switch–1 was on and the load was connected to Phase–A. Once the LT command is received by the end–user controller to transfer the load from Phase–A to Phase–B, it will block the gate signals for switch–1. However, switch–1 will still continue to supply the load until its forward current is falls below its holding current. Then it will turn–off and gate signals can be applied to switch–2. This lack of timing control for a Triac/thyristor is the main drawback of the proposed STS. Gate Turn–Off Thyristors (GTOs) could be applied but have a complex drivers, are more expensive and have higher conduction losses. These are the main reasons why Triacs/thyristors were chosen for the proposed STS.

IV. PROPOSED LOAD TRANSFER CONTROL

VU at each bus is proportional to the difference between the voltage magnitudes of three phases in that bus. Therefore, to reduce VU in each bus, a method that equalises the amplitude of all three phase voltages can be implemented. This can be easily achieved by transferring the load from the highly loaded phase to the lower loaded phase at that bus. In this way, the magnitude of low–loaded phase will drop while the magnitude of high–loaded phase will increase. This process can be continued until the best VU for all buses along the feeder is achieved. The variations in VU should be monitored to prevent VU increase due to an inappropriate LT. An exhaustive method is used for applying a load change from high–loaded phase to low–loaded phase in each bus followed by calculation of VU for all buses. The LT which has resulted in the best VU for all buses in the network is chosen as the desired LT result. The flowchart of the control algorithm is shown in Fig. 1(c).

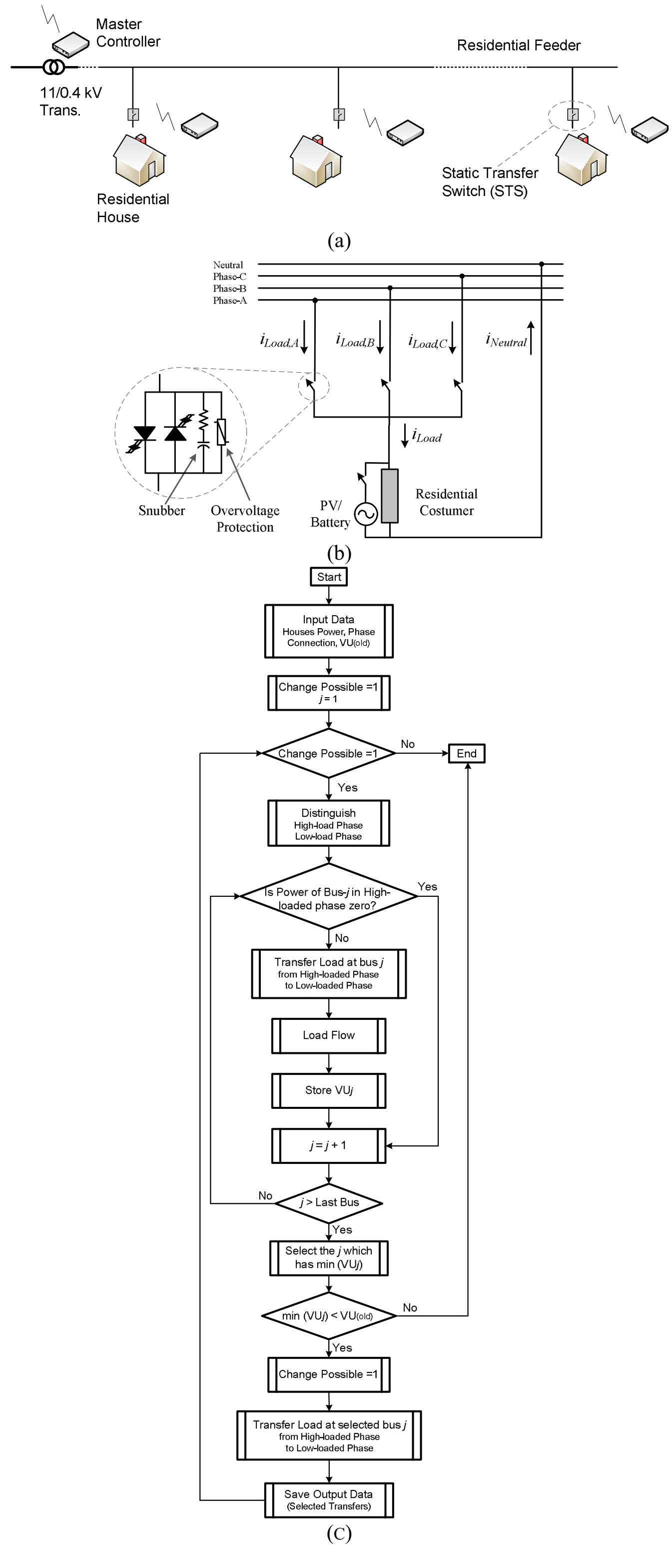


Fig. 1. (a) Schematic diagram of the proposed load transfer scheme in LV feeders, (b) schematic diagram of STS switch, (c) LT control flowchart.

It must be noted that this result is not the globally optimum result. The main advantage of this method is few load transfers are required. VU reduction in the network is the main objective function in this process. Although voltage rise and drop and three–phase power mismatch problems will be improved they are not included in the objective function. This is more fully explained in Section VI.

V. Simulation Results

A MATLAB–based simulation was conducted on a LV residential distribution feeder network with an arbitrary number of houses. Only one distribution transformer Fig. 1(a) is considered. It is assumed that the LV feeder is radial and has a length of 400 m and 30 houses are supplied from that transformer. The houses are connected to 10 buses with equal separations along the LV feeder (i.e. 1 house per phase per bus). The active and reactive data are the real residential data retrieved from the smart meters installed in a suburban area in Perth, Australia. Each house has a load between 0–3 kW. The network is modelled as accurately as possible based on the available network data. In this study, we have developed an unbalanced load flow analysis based on backward/forward sweep concept for a radial three–phase four–wire system.

In this case, the three–phase voltage profile of the feeder before and after 3 LTs is shown in Fig. 2(a). The VU profile along the feeder is shown for the initial case and after 3 LTs in Fig. 2(b).

Fig. 3(a) shows the maximum of VU along the feeder in each 15–min time interval before and after LT scheme application. From this figure, it can be seen that the LT scheme is highly successful in reducing the VU all along the feeder in the 24–hr period. For the studied data, the maximum of network VU was 2.23% which was reduced down 0.16% after LT was applied in that period. After the LT scheme is applied, the maximum of experienced VU along the feeder, in 24–hr period, is 0.77%.

The minimum voltage all along the feeder for each time interval is also shown in Fig. 3(b) for the case before and after LT scheme application. As it was expected, the minimum voltage of the feeder is improved. As an example, the minimum voltage in the feeder in the case without LT scheme was 0.97 pu which was increased to 0.99 pu.

In a similar way, the maximum voltage all along the feeder for each time interval is shown in Fig. 3(c) for the case before and after LT scheme application. As it was expected, the maximum voltage of the feeder is reduced. However, it is to be noted that these changes are the consequence of VU reduction and are not controlled directly.

(a)

(b)

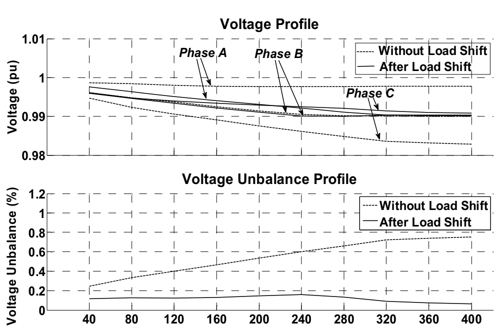
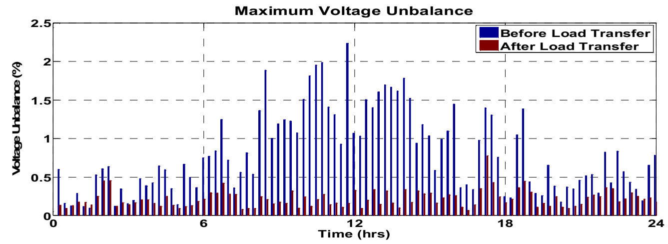
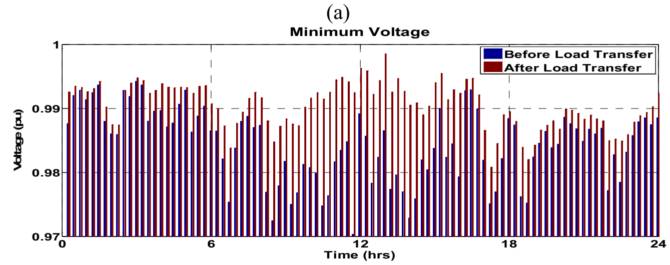


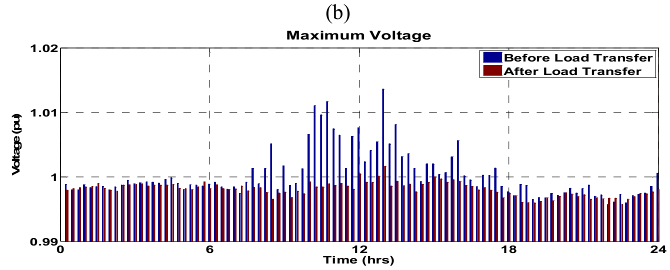
Fig. 2. The network before and after load transfer scheme: (a) Voltage profile, (b) Voltage unbalance profile.



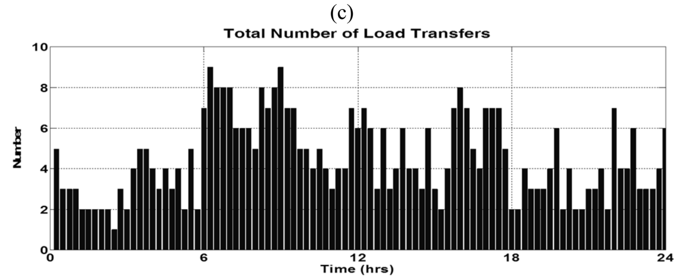
(a)



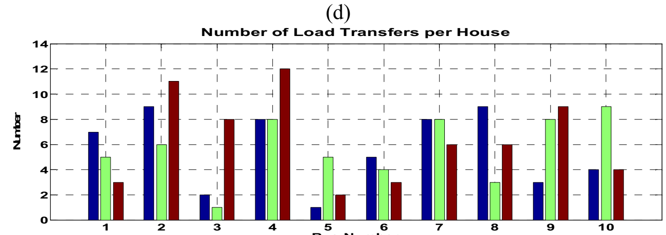
(b)



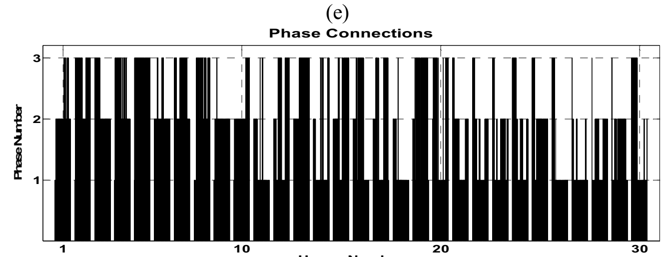
(c)



(d)



(e)



(f)

Fig. 3. Results of load transfer scheme application in 24–hr:
(a) Maximum voltage unbalance in LV feeder before and after LT,
(b) Minimum voltage magnitude in LV feeder before and after LT,
(c) Maximum voltage magnitude in LV feeder before and after LT,
(d) Total number of LTs in each switching case (15–min time intervals),
(e) Total number of load transfers per each house,
(f) Demonstration of phase connection of each house.

It is important to investigate the number of LTs in each switching case. It is highly desirable to achieve better results with fewer LTs. Fig. 3(d) shows the total number of LTs in each switching case. It can be seen that total LT number was between 1 and 9 in each switching case. This means that in the worst case, the LT was applied to maximum of 30% of the houses.

It is highly interesting to investigate if there might be some houses in the network which had more LTs applied to them. Fig. 3(e) shows the total number of LTs for each house at each bus of the network. From this figure, it can be seen that all houses had approximately an equal participation level in the LT scheme. In Fig. 3(f), the phase connection of each house is shown during the 24–hr period. In this figure, Phase–A, B and C are respectively labelled as Phase–1, 2 and 3.

C. Dynamic Simulation Results

For studying the dynamic performance of the proposed LT scheme using STS, the diagram in Fig. 1(b) is modelled in PSCAD/EMTDC. It is assumed that a single–phase 2 kW load with power factor of 0.95 is supplied by a three–phase 240 V RMS voltage through a STS, as described in Section IV. First, let us assume the load is being supplied from Phase–A. At t = 0.5 s, a command is received from the main controller to the end–user controller to transfer the load to Phase–B followed by another command at t = 1 s to transfer the load to Phase–C. The load instantaneous voltage and current waveforms are shown in Fig. 4(a) and (b) while their RMS values are shown in Fig. 4(c) and (d). The instantaneous current waveform is scaled up in this figure for better presentation.

Now, let us assume the load is 1 kW while a PV generating 2 kW power is connected within the residential promises. This will result in a negative 1 kW demand for the load. Fig. 4(e) shows the active power demand of the load while similar LT command is applied. The simulation results verify the successful dynamic performance of the proposed STS based LT for residential applications.

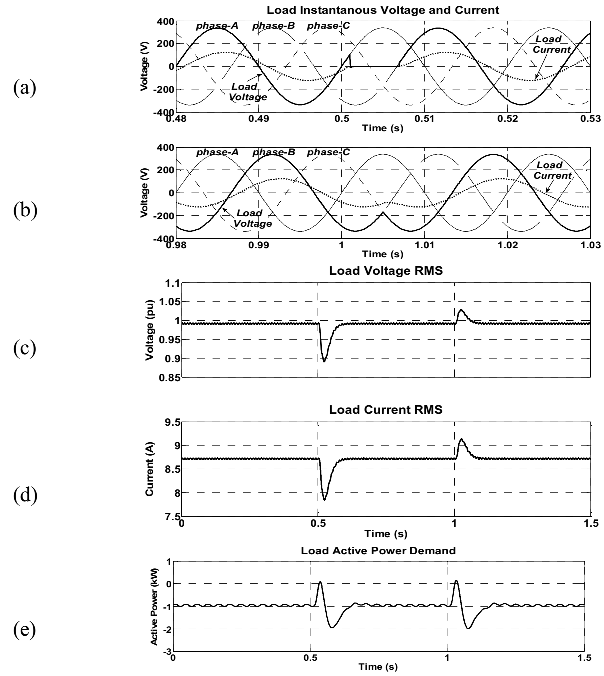


Fig. 4. Dynamic results for Static transfer switch:
(a) Load instantanous voltage at t = 0.5 s from Phase–A to Phase–B,
(b) Load instantanous voltage at t = 1 s from Phase–B to Phase–C,
(c) Load voltage RMS,
(d) Load current RMS,
(e) Load active power demand in presence of a PV.

VI. CONCLUSION

An intelligent dynamic residential LT scheme was proposed in this paper. Each house could transfer its power supply from one phase to another based on the commands from the main controller. The main controller utilizes the proposed high–loaded to low–loaded phase transfer for VU reduction in the three phases. The efficacy of the proposed LT scheme was verified through MATLAB and PSCAD/EMTDC simulations.

REFERENCES

[1] A. Ghosh and G. Ledwich, *Power Quality Enhancement using Custom Power Devices*, Kluwer Academic, 2002.

[2] T. A. Short, *Electric Power Distribution Handbook*, CRC Press, 2004.

[3] F. Shahnia, R. Majumder, A. Ghosh, G. Ledwich and F. Zare, "Voltage imbalance analysis in residential low voltage distribution networks with rooftop PVs," *Electric Power Systems Research*, Vol. 81, Issue 9, pp. 1805–1814, Sept. 2011.

[4] F. Shahnia, A. Ghosh, G. Ledwich and F. Zare, "Voltage unbalance sensitivity analysis of plug–in electric vehicles in distribution networks," 21st Australasian Universities Power Engineering Conf. (AUPEC), pp.1–6, Sept. 2011.

[5] F. Shahnia, A. Ghosh, G. Ledwich, and F. Zare, "Voltage correction in low voltage distribution networks with rooftop PVs using custom power devices," 37th Annual IEEE Industrial Electronics Society Conference (IECON), pp. 991–996, Nov. 2011.

[6] T.H. Chen, J.T. Cherng, "Optimal phase arrangement of distribution transformers connected to a primary feeder for system unbalance improvement and loss reduction using a genetic algorithm," *IEEE Trans. On Power Systems*, Vol. 15, No. 3, pp. 994–1000, Aug 2000.

[7] A. Ghosh, "Performance study of two different compensating devices in a custom power park," *IEE Proc. Generation, Transmission and Distribution*, Vol. 152, No. 4, pp. 521– 528, July 2005.

[8] F. Shahnia, M.T. Wishart, A. Ghosh, G. Ledwich and F. Zare, "Smart demand side management of low voltage distribution networks using multi–objective decision making," *IET Generation Transmission Distribution*, Vol. 6, Issue 10, pp. 986–1000, Oct. 2012.

[9] A.K. Singh, G.K. Singh and R. Mitra, "Some observations on definitions of voltage unbalance," 39th North American Power Symposium (NAPS), pp. 473–479, Sep./Oct. 2007.

[10] M.T. Bina, A. Kashefi, "Three–phase unbalance of distribution systems: Complementary analysis and experimental case study," *International Journal of Electrical Power and Energy Systems*, Vol. 33, Issue 4, pp. 817–826, May 2011.

[11] H. Pezeshki and P. Wolfs, "Correlation based method for phase identification in a three phase LV distribution network," 22nd Australasian Universities Power Engineering Conference (AUPEC), Sept. 2012.

[12] S.S.S.R. Depuru, W. Lingfeng, V. Devabhaktuni and N. Gudi, "Smart meters for power grid: Challenges, issues, advantages and status," *Renewable and Sustainable Energy Reviews*, Vol. 15, Issue 6, pp. 2736–2742, Aug. 2011.

[13] M.E. Kantarci and H.T. Mouftah, "Supply and load management for the smart distribution grid using wireless networks," IEEE Japan–Egypt Conference on Electronics, Communications and Computers (JEC–ECC), pp.145–150, March 2012.