CHEMICAL ENGINEERING TRANSACTIONS

VOL. 45, 2015

A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216

DOI: 10.3303/CET1545048

Carbon Footprint Reduction via Voltage Asymmetry Compensation of Three-Phase Low Voltage Grid Utilizing Small Domestic Power Plants

László Neukirchner, Attila Göllei, Péter Görbe, Attila Magyar*

Department of Electrical Engineering and Information Systems, Faculty of Information Technology, University of Pannonia, Egyetem street 10, H-8200, Veszprém, Hungary
magyar.attila@virt.uni-pannon.hu

The three-phase unbalance problem can introduce additional losses in distribution networks due to both negative and zero sequence components, which leads to inefficient power consumption and increased CO_2 emission of low voltage transformer area, moreover it causes safety possible malfunction of energy transportation networks. The aim of this paper is to examine two new analytical approaches to the voltage asymmetry phenomena and the following power losses and based on this definitions novel control algorithms are suggested and examined in simulation environment. To perform the analysis a power distribution system's Matlab/Simulink model will be created with a domestic size complex energetic system with a power storage module and with renewable sources in a household environment. Based on the novel compensation control algorithm we calculate the possible CO_2 emission reduction and carbon footprint.

1. Introduction

Formerly significant portion of households were connected to the low voltage grid with single phase connection through single phase power meter. Nowadays electricity providers prefer three phase connection in order to achieve more symmetrical load typing. Against this most of the household loads are single phase devices (for example lighting goods, household appliances as washing machines, irons, televisions, personal computers etc.), and with the exception of some optimal case, they are not evenly distributed between the phases. The situation is further exacerbated by the stochastic switching of this type of appliances. This causes stochastic disturbing unbalance in the load currents which cases unbalances load of the low voltage transformer, and causes amplitude and phase unbalance in the voltage phasor trough the serial impedance of the low voltage transportation line wires and connecting devices (Henrik et al. 2014).

Nominal generators supply three-phase sinusoidal positive sequence voltages, which are balanced in terms of their amplitudes phase differences at a single frequency. Any deviations from these two basic characteristics will introduce unbalanced condition. Many countries have changed their regulating laws about power supply to allow for grid-tie inverter systems to provide spare power from renewable sources to local low voltage grids. The unbalance situation further exacerbated by using single phase grid tie inverter systems in the size of typical small household power plants (SHDPP) (1 - 5 kW) and the produced electrical power from renewable power source, wind and solar, stochastic behaviour too (Damian et al. 2014).

Manufacturers currently being introduced their three phase grid synchronized inverters in this size to the market to lower the unbalance caused the spare power asymmetrical current injection to the low voltage grid. The uniform distribution of loads and generators can lower this effect, but the limited number of households in one transformer area is unable to statistically equalize the stochastic behaviour of loads and sources. Rising number of SHDPP can amplify this disturbances. This unbalance cause suboptimal operation of low voltage three phase transformers to create undesirable additional power loss and CO_2

Please cite this article as: Neukirchner L., Göllei A., Görbe P., Magyar A., 2015, Carbon footprint reduction via voltage asymmetry compensation of three-phase low voltage grid utilizing small domestic power plants, Chemical Engineering Transactions, 45, 283-288 DOI:10.3303/CET1545048

emission rising, to increase the calculated carbon footprint of an average household and increase in the probability of malfunction of low voltage energy transportation system.
The terminology of unbalanced can be divided into amplitude unbalance, phase difference unbalance, and unbalanced harmonic disturbances. Occurrence of at least one of these features is enough for a distribution network to become unbalanced. Unbalance condition could lower stability margin, increasing the power losses. A small voltage unbalance might lead to a significant current unbalance because of low negative sequence impedance (Görbe et al. 2011).

2. Regulated indicators of voltage asymmetry

The voltage unbalance is becoming more a vital issue as there are more and more customers using single-phase capacitive loads and single phase generators width renewable sources. Although on the meaning of the term voltage unbalance, where different standards introduce different conventional definitions as follows Eq(1):

$$\begin{aligned}
V_{936} &= \frac{max\{V_{an}, V_{bn}, V_{cn}\} - min\{V_{an}, V_{bn}, V_{cn}\}}{mean\{V_{an}, V_{bn}, V_{cn}\}} \times 100 \\
V_{112} &= \frac{\text{max deviation from mean of}\{V_{an}, V_{bn}, V_{cn}\}}{\text{mean}\{V_{an}, V_{bn}, V_{cn}\}} \times 100 \\
MDV &= \frac{\text{max deviation from mean of}\{V_{ab}, V_{bc}, V_{ca}\}}{\text{mean}\{V_{ab}, V_{bc}, V_{ca}\}} \times 100 \\
TDV &= \frac{negative\ sequence\ voltage}{positive\ sequence\ voltage} \times 100
\end{aligned} \tag{1}$$

where V_{an}, V_{bn}, V_{cn} are the phase-to-neutral voltages, V_{ab}, V_{bc}, V_{ca} are the line-to-line voltages, is equal to the voltage amplitude of the fundamental frequency and is the voltage amplitude of the n-th harmonic. Although the harmonic distortion (Görbe et al. 2011) does not relate closely to the asymmetry phenomenon, it can cause a variety of problems like dropping efficiency of electric motors.
The above four definitions could produce different values for a single cases (current unbalance formulations are simply obtained by replacing voltage with current components). The first two standards ignore the 120 degree phase difference unbalance and only take the amplitudes into account. The last two definitions, MDV and TDV, are sensitive to the phase difference unbalance. Nevertheless, these definitions ignore zero sequence components and harmonic distortion that are always present in three-phase four-wire systems (Tavakoli et al. 2011).

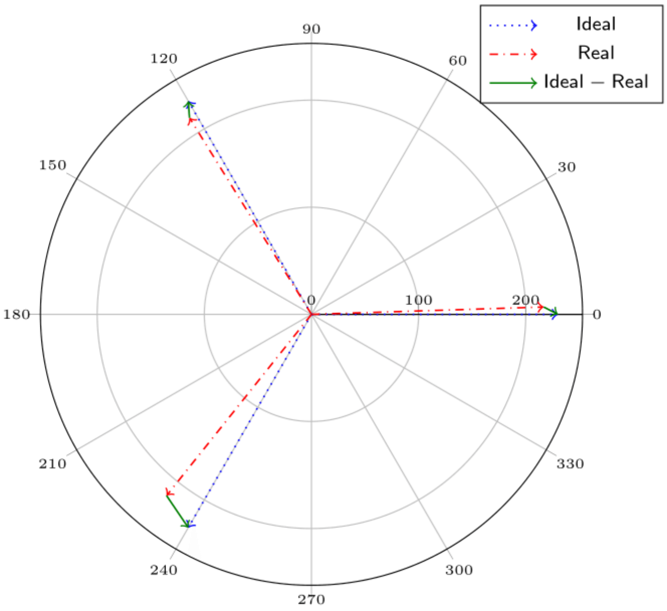

Figure 1: Calculation of vectorial norm displayed on polar coordinate system

3. Novel norm for measuring voltage asymmetry

It is possible to create a numeric error model to obtain each vector's differences form the ideal, and calculate the vectorial error's mean. The two main advantage of this method (Figure 1) are that all forms of differences are taken into account, and computationally less demanding than the prescribed efficient geometrical methods. The calculation method is as follows Eq(2):

$$\begin{aligned} \Delta R &= 230e^{j0} - R_{phase} \\ \Delta S &= 230e^{j120} - S_{phase} \\ \Delta T &= 230e^{j240} - T_{phase} \\ N &= |\Delta R \Delta S| + |\Delta R \Delta T| + |\Delta S \Delta T| \end{aligned} \tag{2}$$

where $\Delta R, \Delta S, \Delta T$ are the vectorial error of each phase, and N is the absolute value of the cross-scalar products of the errors.

4. Asymmetry compensation control

4.1 Low voltage power grid model

The mathematical model of the nonlinear distorted network was simulated in Matlab Simulink using the Power Electronics Toolbox (see Figure 2). The flow chart of the model consists of a small 400 V, 50 Hz transformer station. Only the secondary windings modelled, due to the ideally prescribed states of the medium voltage grid. (The other reason was, to perform measurements and current intervention in a domestic measurement point.). Power distribution cable networks were the nonlinearities was implemented with serial resistive and inductive elements as well as capacitive couplings, and domestic load system. Three types of loads were modelled: Ohmic loads (representing e.g. heating devices and traditional bulbs, ohmic loads with serial inductances (representing e.g. motors and rotating household appliances) and capacitive input stage loads representing simple nonlinear switching mode power supplies (see Figure 3). At this stage the model of the inverter block was not created, but rather controlled current sources were implemented as actuators.

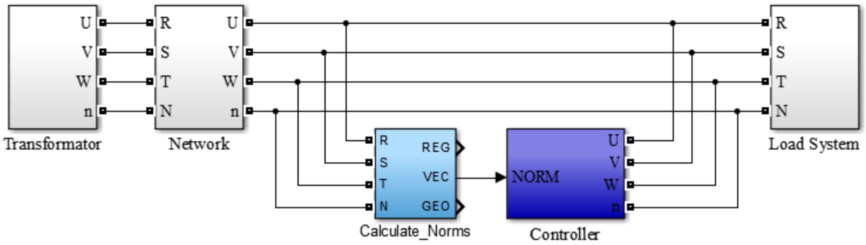

Figure 2: Flow chart of low voltage three phase grid model

4.2 The controller Structure

In the real application the grid tie inverters connected to the low voltage network normally cannot sense the exact three phase voltage and current time functions on the transformer secondary connection, but only the voltage time functions at the connection point, behind the power meter of the household. Sensing the needed voltage and current values has technical and legal difficulties. Some of them will be overcome in the near future using smart grid interfaces between the provider and the end user appliances. Now only the voltage measurement is feasible, so a control structure had to be used. We should conclude the actual voltage and current asymmetry of the transformer from the connection point voltage status. The problem is that, the exact mathematical relation is nonlinear because the nonlinear, and highly time variant loads of the network, we should use a control strategy to cope this nonlinear and time variant energy system. For this purpose we chose an asynchronous parallel pattern search method (Asynchronous Parallel Pattern Search, or APPS) which could be able to control our scenario. We applied a variant of the gradient method that is a first-order optimization (minimization) algorithm for a multivariate function $f(x)$. The point $x(k)$ corresponding to the local minimum can be calculated from the negative gradient $\Delta f(x)$, that gives the value and direction of the corresponding step in the parameter space. The next step is made in the direction of gradient with the proper sign. This sequence of steps Eq(3), ideally, converges to local multivariate extreme value $x(k)$ of the function (Snyman et al. 2005).

$$x(k) = x(k-1) - t_k \cdot \Delta f\big(x(k-1)\big),\ k = 1,2,\dots,n\ . \qquad (3)$$

The controlled electrical system is described by multivariate non-linear differential equations, the optimization of which is infeasible to derive using the differentiation of an error function. Therefore, the optimization methods based on direct differentiation are not applicable. In such cases, when high computational power is needed for performing long time-consuming simulations, the APPS method can utilized. The search pattern p is based on the sampling of the error function (selected norm) on a "grid", and it corresponds to variables or subsets of variables in each point in the independent variable or parameter space easily. At the same time, the norm values at these points can be calculated independently (Polyak 1987) Eq(4).

$$iff\ \Delta k > 0,$$
$$x(k+1) = x(k) + \Delta k \cdot d_i\ if\ f(x(k) + \Delta k \cdot d_i)\ \leq f\big(x(k)\big), k = 1,2,\dots,n\ , \qquad (4)$$

where the parameter is $x(k)\ \in\ R_n$, and the search pattern $p\ \in\ D\ =\ \{d_1,\dots d_n\}$ is taken from a predefined finite set. In this case, the error function values should be calculated for each pattern p in the set D. If the error function is not decreasing in any of the directions, then the step size should be reduced (e.g. by half). As the competing directions are different, if there isn't enough computing power available for direction vector p, synchronization should not be maintained. In this case we are talking about the asynchronous case (Kolda et al. 2001). In the case of our controller, an individual p vector is defined for each output variable, and the optimization was performed in each direction asynchronously and shifted in time. As being prescribed, the full state-space model was not available in analytic form, and the differential equations describing the system are not linear. Most likely, the error function has a single local minimum as a symmetric amplitude and phase values. Approaching the minimal value of norm, the controller uses adaptive increments that are proportional to the norm itself. Because of the complex interactions between the components of the controller, only one parameter is changed at a time, even if the values of the amplitude and phase components in specific time slot changes. The algorithm moves along the six axes of six separate time slots close to the local minimum of the error function. Each time slot is six period (120 ms) long. The controller frequently initiates a 20 ms up and down step function with two relaxation cycles. In each iteration only one physical value is changeling of the three injected current amplitude and three phase values. If the change decreases the cost function (the reference norm's normalized value), the controller holds the new value of amplitude or phase for the controlled current sources (Kolda et al. 2001).

4.3 Controller Performance

At the beginning of the simulation we examined the static performance of the proposed controller as a verification of the method. The controller starts at t = 2 s to operate and compensate the asymmetries via the vectorial asymmetry indicator as cost function (see Figure 3.). At Figures 4 and 5 it can be seen the controllers intervention to the network with the controlled current's amplitudes and phases. The global reactive power reduction per phase can be seen Figure 5. The values per reactive power per phase start to reduce after the start of the controller algorithm.

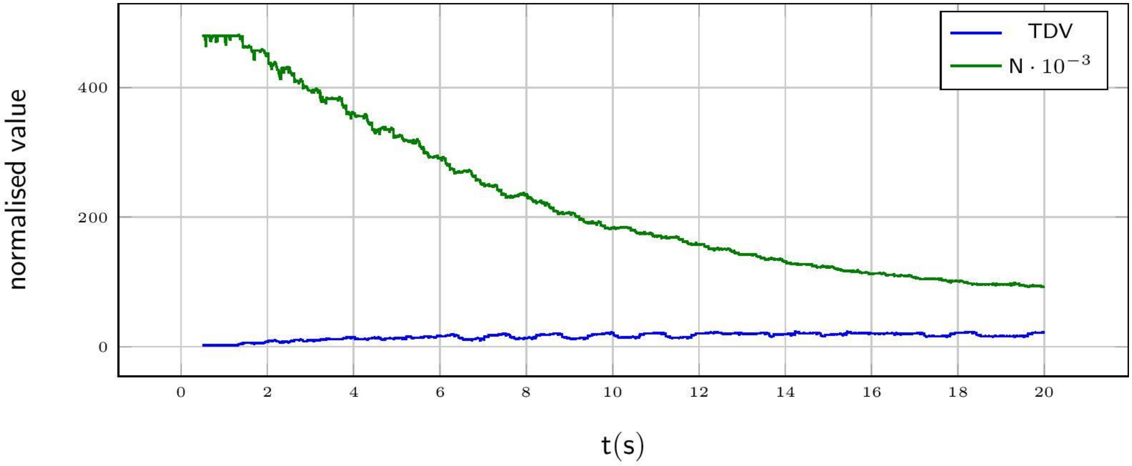

Figure 3: Values of the prescribed norms during control

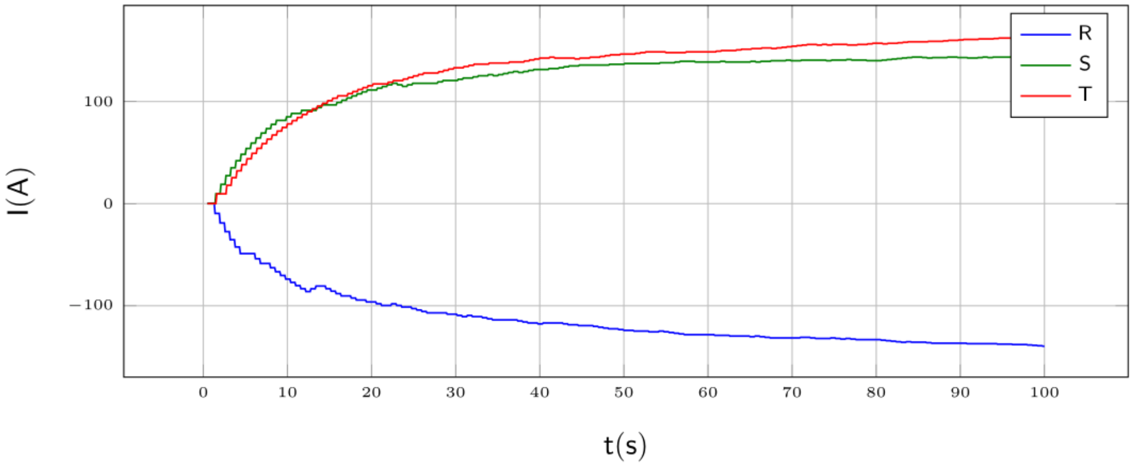

Figure 4: Intervention width current amplitudes

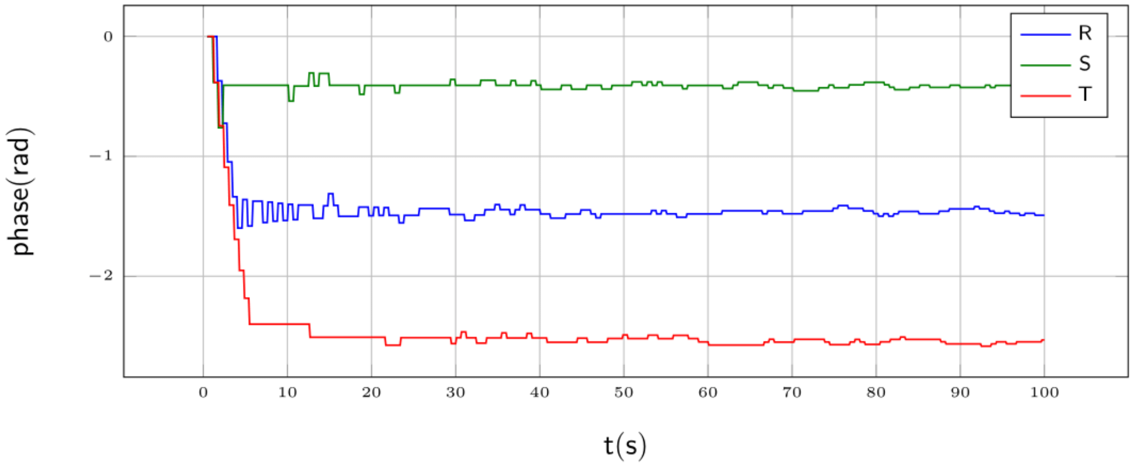

Figure 5: Intervention width current phases

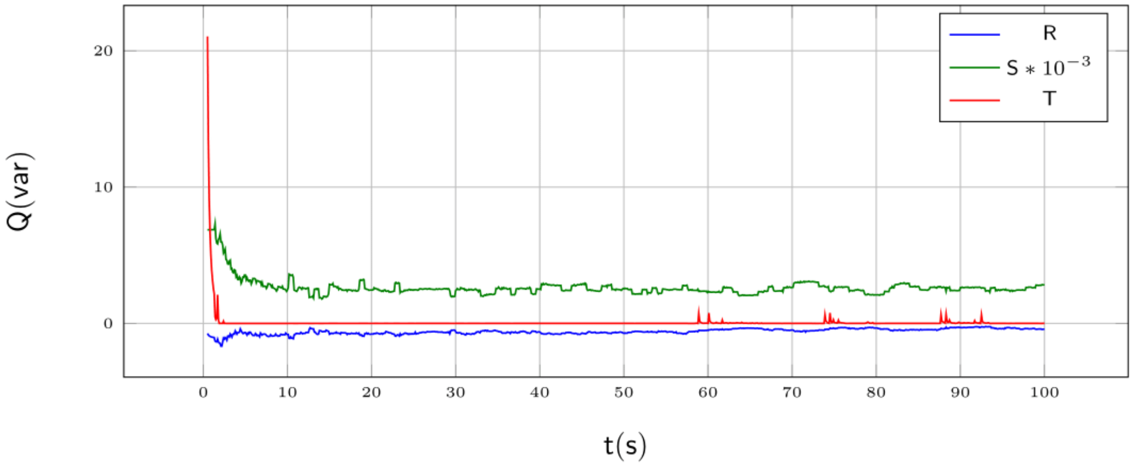

Figure 6: Reduction of reactive power per phase during control

5. Conclusion

A novel norm for describing the voltage asymmetry present in three phase electrical networks has been presented in this work. The value of the norm can be computed effectively, even in real time, i.e. it is a good candidate for a cost function of a complex controller responsible for minimizing voltage asymmetry. The norm has also been tested in a simulation environment involving a modelled electrical grid, a domestic power plant, and several loads of different types. The control algorithm is a version of the APPS family, involving a six dimensional parameter space. The preliminary tests show that it was possible to decrease the norm value by 96 %, together with an overall 52.2 % decrease in effective and 60 % decrease in the reactive power. The fact, that this controller enables the reactive power reduction means, that the power loss, CO_2 emission, i.e. the carbon footprint can also be decreased. Using the above results, it can be estimated the environmental effects of voltage asymmetry compensation. Let us assume 3,000 kWh for the yearly electric energy consumption an average household. Given this, nonlinear distortion compensation results in an energy savings of and 255.32 kWh is saved as a result of distributed generation. Taking into account the proportion of power currently generated by fossil fuels(coal 17.3%, gas 38.3% (MVM, 2008)) and the rate of CO_2 emission during electric energy production (1,000 g kWh 1 from coal and 430 g/kWh from gas), we can conclude that voltage asymmetry compensation could reduce CO_2 emissions by 86,221.5 g y, in an average household. (Görbe et al. 2011) Note, that the asymmetry values on the network have been set extraordinary high, to demonstrate the capabilities of the controller.

References

Görbe P., Magyar A., Hangos K. M., 2012, Reduction of power losses with smart grids fuelled with renewable sources and applying EV batteries, Journal of Cleaner Production, vol. 34, 125-137.

Görbe P., Fodor A., Magyar A., Hangos K. M., 2014, Experimental study of the nonlinear distortion caused by domestic power plants, Applied Thermal Engineering, 70(2), 1288-1293.

Kolda T.G., Hough P.D., Torczon V.J., 2001, Asynchronous parallel pattern search for nonlinear optimization, Society for Industrial and Applied Mathematics: Journal on Scientific Computing, 23(1), 134 – 156.

Lund H., Mathiesen B.V., Connolly D., Østergaard P. A., 2014, Renewable energy systems - A smart energy systems approach to the choice and modelling of 100 % renewable solutions, Chemical Engineering Transactions, 39, 1-6.

Giaouris D., Papadopoulos A. I., Seferlis P., Papadopoulou S., Voutetakis S., Stergiopoulos F., Elmasides C., 2014, Optimum energy management in smart grids based on power pinch analysis, Chemical Engineering Transactions, 39, 55-60.

Polyak B.T., 1987. Introduction to optimization, Publications Division, New York, USA.

Snyman J. A., 2005. In Practical mathematical optimization: An introduction to basic optimization theory and classical and new gradient-based algorithms. Springer, New York, USA.

Tavakoli Bina M., Kashefi A., 2011. Three-phase unbalance of distribution systems: Complementary analysis and experimental case study, International Journal of Electrical Power & Energy Systems, 33(4), 817-826.