Voltage Unbalance Reduction in the Domestic Distribution Area Using Asymmetric Inverters

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Abstract

Voltage unbalance is a major yet often overlooked power quality problem in low voltage residential feeders due to the random location and rating of single-phase renewable sources and uneven distribution of household loads. This paper proposes a new indicator of voltage deviation that may serve as a basis of analysis and compensation methods in this dimension of power quality. The paper proposes three main results. First of all a novel voltage norm capable of indicating unbalance and under-voltage in a single value. Afterwards, a three phase unbalance reduction controller structure is given. As the third main result, the proposed controller structure is integrated with an optimization based control algorithm that uses asynchronous parallel pattern search as its engine. The suggested structure and the underlying three phase power grid model has been implemented in a dynamical simulation environment and tested against engineering expectations.

The simulation based experiments served as a proof of concept for the

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proposed complex control structure. The experiments included performance and robustness analysis, both of them concluded that the proposed control and inverter structure is promising.

The proposed three phase inverter structure together with the control algorithm connected with a renewable source (photovoltaic panel or wind turbine) is capable of an asymmetric power injection or rerouting the energy flow to the grid so that the voltage unbalance decrease. This is also important from the environmental point of view since the achieved power loss reduction can easily be translated to CO_2 emission reduction and carbon footprint - these indicators has also been calculated.
Keywords: electrical grid, power quality, loss reduction, optimization, control

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1. Introduction

Recently, due to the growth of distributed generation from renewable energy sources the nature of the electrical power grid tends to alter from a passive network to an active one. In this new environment, the importance and difficulty of maintaining the security and operational stability of the distribution system are increasing together. As opposed to this expectation most of the household renewable sources and loads are unevenly distributed single phase power converters, some of them representing high power consumption. Ideal generators supply symmetrical three-phase sinusoidal positive sequence voltages, which are balanced in terms of their amplitudes phase differences at a single frequency. The terminology of unbalance can be divided into amplitude unbalance, phase difference unbalance, and unbalanced harmonic disturbance. The occurrence of at least one of these features is enough for a distribution network to become unbalanced. The situation is further exacerbated by the stochastic on/off switching of the different types of loads which causes stochastic disturbing unbalance in the load currents which cases unbalanced 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 cables. 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 of the grid is further increased by using single phase grid tie inverter systems in the size of typical small household power plants (1 - 50 kW) and the produced electrical power originating from renewable power source (wind and solar) also admits stochastic behavior. This unbalance yields to a suboptimal operation of low voltage three phase transformers to generate undesirable additional power loss and increase in the probability of malfunction of the low voltage energy transportation system. The effective current unbalance causes additional power loss of the transportation line resistances too.

Single phase power injections to the grid are mainly generated by domestic photovoltaic-(PV) and wind power plants. Many current references about the renewable energy sources integration to the low voltage grid ad short time and long time storage ready for connection of this electrical energy in the literature can be found. For off-grid solutions sometimes more complex solutions integrating diesel generators, PV and wind generators are proposed, e.g. in Shezan et al. (2016). Cucchiella et al. (2013) were presented the economical aspects of a PV system. The economic results are strongly influenced by the annual average insolation value, which encourages the areas most exposed to the sun and the southern areas. The consumption of consumers is not critically important, but the design principle used has as significant effect on the maximization of the performance of PV plants. Kaldellis et al. (2009) notify, that autonomous photovoltaic systems are strongly responsible of their reactive energy requirements. To support photovoltaic systems with battery banks sustainable character one should be able to establish that their reactive energy requirement share fairly compensated by the corresponding energy yield. Additionally, Ortega et al. (2013) emphasize that PV systems are increasingly being deployed in all over the world, and this is the source of a wide range of power quality problems. With a view to consistently measuring and assessing the power quality characteristics of PV systems, they had presented an in-depth overview and discussion of this topic. The study by Huat et al. (2015) explored integration issues of electric vehicle battery packs. They suggest that high voltage battery packs with large format cells has advantages in assembly, thermal management, monitoring and control, services and maintenance. On the other hand, quality, reliability and limited specific energy of large format cells are obstacles need to overcome. Solving these problems will further affect the cost, performance, reliability and safety of the electric vehicles. Smart energy systems in specially in urban areas are discussed in Lund et al. (2015) where a design methodology has been suggested.

There are different consequences of unbalance. Lee et al. (1998) were discussing the effects of unbalanced voltage on a three-phase induction motor, one has to consider not only negative-sequence voltage but also the positive-sequence voltage. With the same voltage unbalance factor, the status of voltage unbalance could be judged by the magnitude of positive sequence voltage. Also the effect of voltage unbalance has been studied on three-phase four-wire distribution networks for different control strategies for three-phase inverter-connected distributed generation units on voltage unbalance in distribution networks (Meersman et al. (2011)). Here the negative-sequence component and the zero sequence component were studied where unbalance conditions could lower stability margin and increasing the power losses. On the other hand, the adaptive coordination of distribution systems included distributed generation is also an emerging problem as it was discussed by Ates et al. (2016). A small voltage unbalance might lead to a significant current unbalance because of low negative sequence impedance (Bina and Kashefi (2013)) too. There are different approaches of lowering the unbalance with different control techniques. Additionally, new computationally efficient control techniques have been presented by Lee et al. (2010) to estimate and compensate input voltage-unbalance disturbances for a voltage source converter. These tools are designed to be effective with high power systems with slower PWM switching frequencies of 5 kHz or lower and limited current-controller bandwidth. About the unbalance compensation control aspect, a three-phase IGBT-based static synchronous compensator were proposed for voltage and/or current unbalance compensation by Xu et al. (2010). An instantaneous power theory was used for real-time calculation and control. Three control schemes current control, voltage control and integrated control were proposed to compensate unbalanced voltage, unbalanced current or both.The unbalance phenomena and power quality can be examined with modeling too. A particular modeling method was presented by Li et al. (2005) where a three-phase four-wire grid-interfacing power quality compensator were modeled. During grid voltage unbalance, the compensator, used a shunt and a series four phase inverter, and could enhance both the quality of power within the microgrid and the quality of currents flowing between the microgrid and utility system. The shunt four-leg inverter were controlled to maintain a set of balanced distortion free voltages to regulate power sharing among the parallel-connected distributed generation systems. Simulation studies were carried out by Hu et al. (2016) where one of the aims was to develop and test the feasibility of a decoupled three-phase on-load tap charger in the distribution system with the objective of improving the distribution network power quality. Further control methods were applied for the solution for balancing of the most sensitive with regard to electric energy quality part of power system by Korovkin et al. (2014), minimizing the active power losses, stabilization of three-phase voltages, enhancement of asynchronous machine performance stability and reduction of errors occurring in power consumption measuring circuits. Further control methods were applied for the solution for balancing of the most sensitive with regard to electric energy quality part of power system in Korovkin et al. (2014), minimizing the active power losses, stabilization of three-phase voltages, enhancement of asynchronous machine performance stability and reduction of errors occurring in power consumption measuring circuits.In our Department we have antecedents of research of power quality in low voltage distribution grid. A previous work of Görbe et al. (2012) a complex control unit has been proposed that is capable of lowering extant harmonic distortion. In the work of Görbe et al. (2014) the effect of a small domestic (photovoltaic) power plant on the power quality, mainly the total harmonic distortion has been examined. The aim of this work is to examine and compensate three phase voltage asymmetry of the electrial network based on the extended simulation model proposed by Görbe et al. (2012).

In many articles the authors presents a different viewpoint of calculating unbalance on the network. Martin et al. (2015) showed to assess the harmonic distortion and the unbalance introduced by the different loads connected to the same point of common coupling have been applied to an experimental distribution network. By Kini et al. (2007) the focus was to bring out the ambiguity that crops up when we refer to a particular value of voltage unbalance that exists in the system. By making use of the complex nature of voltage unbalance, the voltage combinations that lead to the calculation of complex voltage unbalance factor could be narrowed down to a great extent. A fast and accurate algorithm for calculating unbalance has been presented by Wen et al. (2014). The magnitudes of zero, positive, and negative sequences are obtained through simple algebraic equations based on the geometric figure, which is also called as 4 and 8 geometric partitions. Also a three-phase optimal power flow calculation methodology has been presented by Araujo et al. (2013), that is suitable for unbalanced power systems. The optimal algorithm uses the primal-dual interior point method as an optimization tool in association with the three-phase current injection method in rectangular coordinates.

2. Basic notions

2.1. Network structure

The examined network is supposed to be the low voltage local transformer area with regular households, depicted in Figure 1. The network structure of Figure 1 has been implemented in Simulink™ environment for simulation based experiments. Most of the households represent a single phase load with resistive inductive and capacitive properties while some of them are symmetric three phase ones. There might also be some households with domestic powerplant, they are not only loads but also represents distributed generators. Furthermore, it is assumed that the households located on a domestic size grid tie inverter are also provided with battery storage capacities. Commercially available inverters are capable of optimizing the working point and charging current of the system, while the ability of power quality improvement is far not typical - it is in experimental phase in some cases, e.g. Görbe et al. (2012).

2.2. Voltage deviations

The paper focuses on three types of voltage deviations. The first fall in to the category of unbalance, namely any kind of phase deviations, and unbalanced amplitude deviations, and balanced amplitude deviations, like under-voltage. There are many different technological causes with more or less practical importance. The following conditions are examined and tested in the sequel:

Single phase under-voltage unbalance If there is a single phase uncompensated overload in the system, the voltage in the overloaded phase

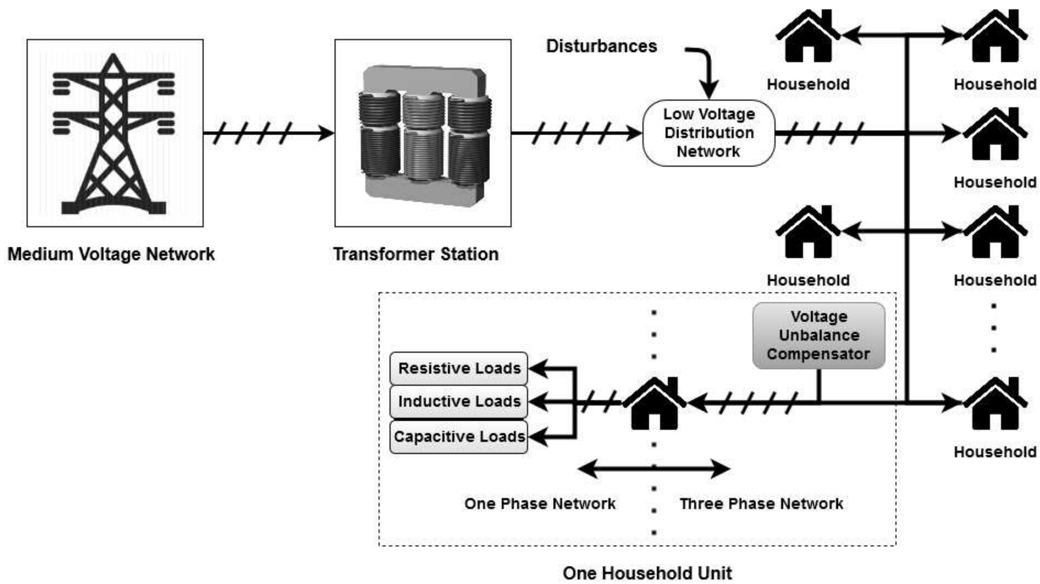


Figure 1: The simplified structure of a three phase four wire low voltage network. The transformer station acts as transition from the medium voltage power grid to the low voltage network. The several regular households are representing the main loads of the network. The transformer and the loads are connected with power line sections infected by inductive and resistive disturbances and capacitive couplings. Domestic powerplants can connect to any connection point within the low voltage network, via an appropriate inverter - either to the three phase sections using a three phase inverter or to a single phase using a single phase inverter.

will be lower than the other two.

Two phase under-voltage unbalance Two of the three phases are overloaded without compensation, the two overloaded phases will have higher voltage drop than the third phase. Balanced three phase under-voltage] The loads of all three phases are overloaded in an unbalanced manner.

Unbalanced single phase angle If the three phase voltage amplitudes are balanced but the relative angles between them (ideally it should be equal to ±120 degree). It is assumed, that phase A would be the reference. If one of the other two phase angles is deflected, unequal displacement.

Unbalanced two phase angles displacement Similar to the single phase angle unbalance, if the other two phase angles are both deflected, then unequal angle displacement in two phase angles occurs.

An indicator of the voltage unbalance is supposed to measure the extent of unbalance but it is not expected to classify between the above types.

2.2.1. Standard indicators of unbalance

Although the term voltage unbalance is unambiguous, the root phenomenon may be various as well as the standard norms used to measure unbalance. All of these different indicators measure voltage unbalance but each of them does it in a different way (4).

$$V_{936} = \frac{\max\{V_{an}, V_{bn}, V_{cn}\} - \min\{V_{an}, V_{bn}, V_{cn}\}}{\text{mean}\{V_{an}, V_{bn}, V_{cn}\}} \times 100 \quad (1)$$

$$V_{112} = \frac{\text{max deviation from mean of}\{V_{an}, V_{bn}, V_{cn}\}}{\text{mean}\{V_{an}, V_{bn}, V_{cn}\}} \times 100 \quad (2)$$

$$MDV = \frac{\text{max deviation from mean of}\{V_{ab}, V_{bc}, V_{ca}\}}{\text{mean}\{V_{ab}, V_{bc}, V_{ca}\}} \times 100 \quad (3)$$

$$TDV = \frac{\text{negative seq.voltage}}{\text{positive seq.voltage}} \times 100 \quad (4)$$

The voltages $\{V_{an}, V_{bn}, V_{cn}\}$ denotes the phase-to-neutral voltages, while $\{V_{ab}, V_{bc}, V_{ca}\}$ are the line-to-line voltages, V_1 is equal to the voltage amplitude of the fundamental frequency and V_n is the voltage amplitude of the n-th upper harmonic voltage Bina and Kashefi (2013) (current unbalance formulations are simply obtained by replacing voltage with current components). Although the harmonic distortion does not relate closely to the asymmetry phenomenon, it might cause a variety of problems like dropping efficiency of electric motors.

The above four norms measure different values for a single case. The first two standard indicators, V_{936} and V_{112}, 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 Bina and Kashefi (2013).

2.2.2. *Proposed geometrical indicator*

It can be stated that every difference between the ideal and the measured voltage in both amplitude phase and sub-harmonics causing a form of voltage deviation. The problem can also be investigated from a geometrical point of view as it is depicted in Figure 2. The three-phase voltage system's phasor diagram contains three phase-to-neutral voltage vectors which can be regarded as the points of a triangle (similarly, the three line-to-line vectors can play the role of the edges of the triangle). The two triangles (i.e. the ideal and the actual ones) always intersect except from very extreme and physically meaningless cases. The area where the two triangles do not cover each other (i.e. the difference of their union and intersection) can be used as a norm of voltage quality. In fact it is computationally more demanding compared to the previous methods, but takes every deviation into consideration Neukirchner et al. (2015a),Neukirchner et al. (2015b). The calculation of error is given by (5).

$$G \quad = \quad \text{Area of } (\triangle_{Ideal} \cup \triangle_{Real} - \triangle_{Ideal} \cap \triangle_{Real}), \tag{5}$$

$\triangle_{Ideal}$ indicates the triangle spanned by the ideal voltage vectors and $\triangle_{Real}$ the triangle of real voltage vectors. Difference of the ideal and the real triangle's union and intersection defines the norm G. Basically, the algorithm calculates the symmetrical difference of the triangles, stretched from three phase ideal and real voltage vectors.

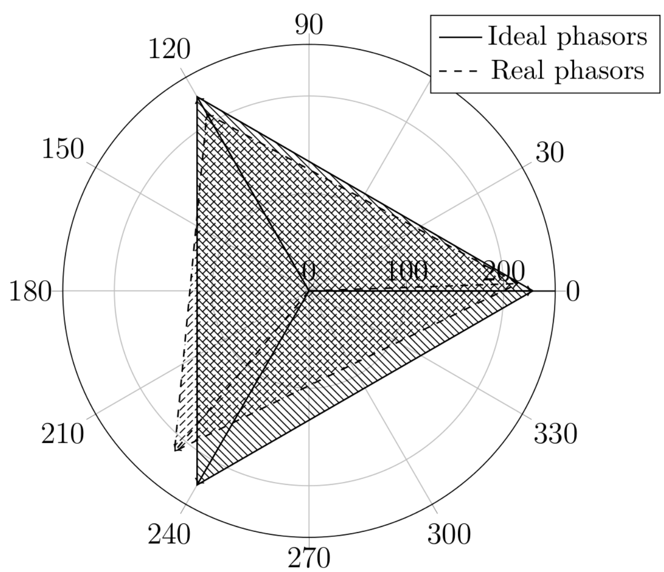


Figure 2: The triangles spanned by the ideal and the actual voltage phasors. The extent of voltage deviation on the network can be measured by the sum of areas where the two triangles are not overlapping.

2.2.3. The geometrical method's additional content compared to the regulated method

When using a new method for calculation and cost function it is reasonable to test it's usability against the prevalent or regulated method. In this case the geometrical norm's utility (5) against the TDV (4) value. The geometrical norm was validated experimentally, by investigating the correlation between the regulated (4) and geometrical (5) norms subjected to random, uniformly distributed unbalance on the voltage vector amplitude and phase values with 20 V amplitude and $1/300 \cdot \pi$ rad phase variance (Fig. 3, and Fig. 4).

Although there is correlation between the two norm values in the general case, but for some situations the regular method indicates low, while geometrical norm still indicates high value.

On Figure 5a dominant phase deviation can be observed, while Figure 5b shows amplitude deviation but with opposite direction. When there is such deviation on the grid both indicators present almost identical results. On 5c there is still observable unbalance (two phase deviate stronger than the third in terms of amplitude), but the correlation is significantly lower. In the last case in the lowest correlation area, amplitude deviation is present, but the deviation direction is identical on all phases (balanced over-voltage or under-voltage)(Figure 5d). The regular method indicates very low values. In this case other methods are utilised in parallel in terms of network diagnostics to detect the under-voltage phenomena.Arnborg et al. (1997).

To clarify this, the regular norm's calculation method needs to be investigated. The symmetrical component mutual impedance matrix on a three

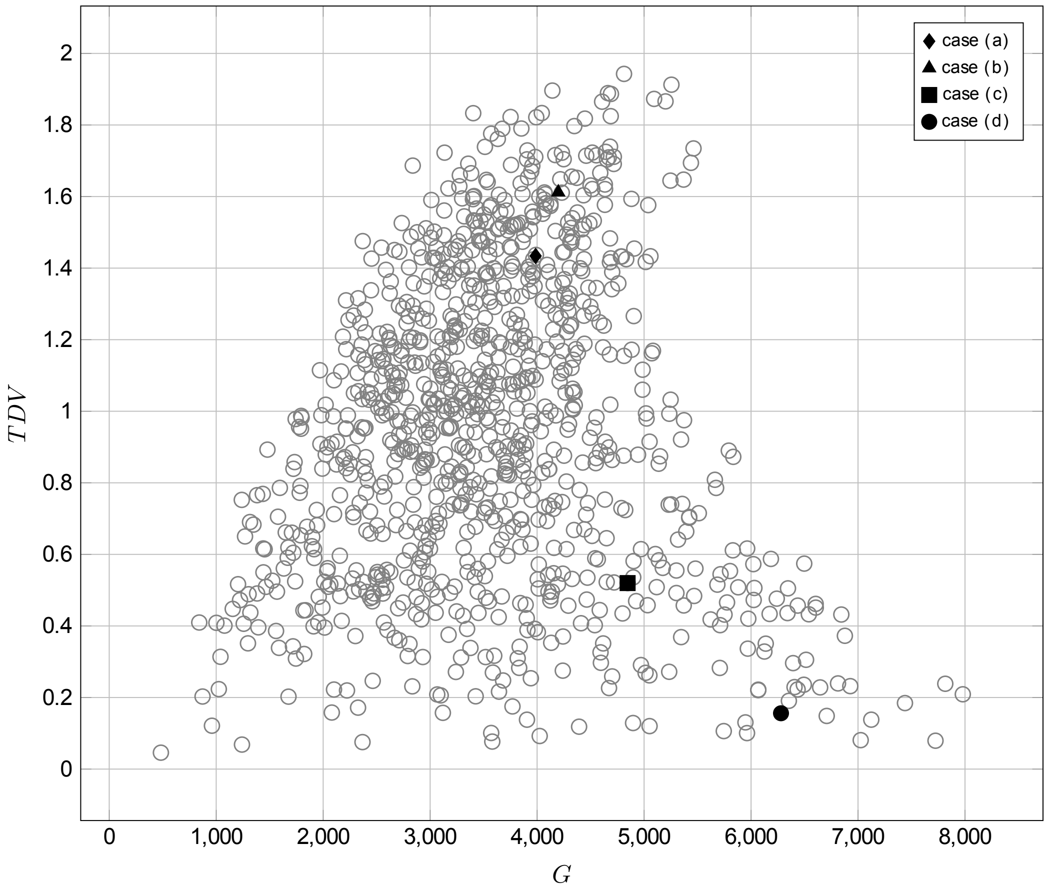


Figure 3: Correlation between the geometrical voltage unbalance indicator G and the regulated voltage unbalance indicator TDV using 1000 samples. In every iteration each three phase voltage vector's amplitude and phase values changed randomly, according to uniform distributions with ± 20 V and $\pm\frac{1}{3}\pi \cdot 10^{-2}$ rad variance. It can be seen, that the geometric norm contains more information than the classical one. The four asymmetry cases of Figure 5 are denoted by black symbols on the picture. It is apparent, that in case (c), and (d) the G norm holds additional information than the TDV.

phase connection point is given by (6),

$$
\begin{aligned}
Z_s &= \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \cdot \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \cdot \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} = \\
&= \begin{bmatrix} Z_{00} & Z_{01} & Z_{02} \\ Z_{10} & Z_{11} & Z_{12} \\ Z_{20} & Z_{21} & Z_{22} \end{bmatrix},
\end{aligned} \tag{6}
$$

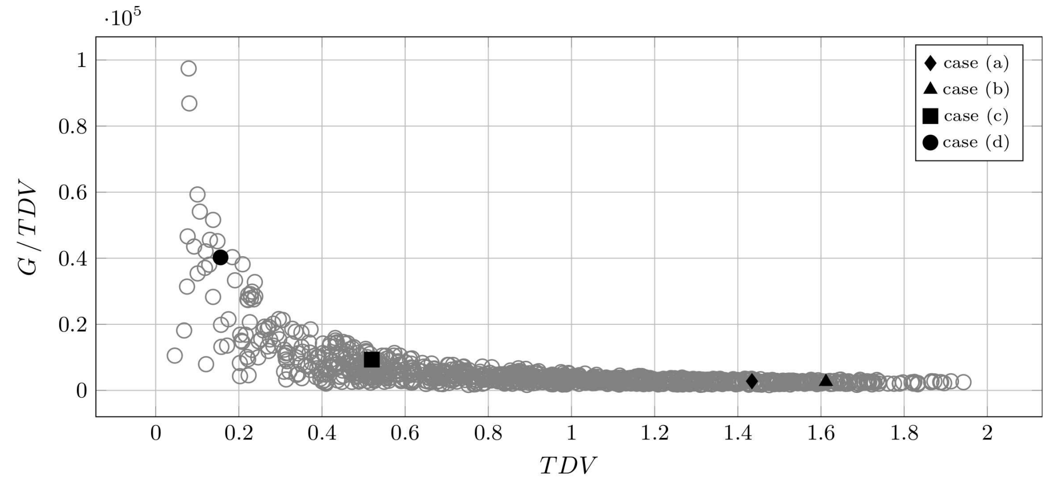
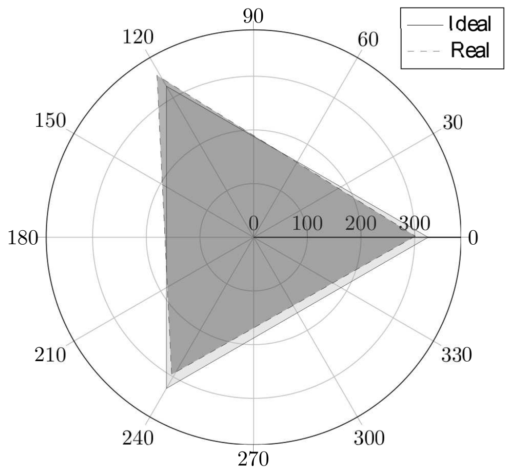


Figure 4: **Itt a .eps converzio nem lett valami jo, javitani kell!** Correlation between the regulated unbalance indicator and the fraction of geometrical and regulated indicator. It can be seen that there is a functional connection between the two values.

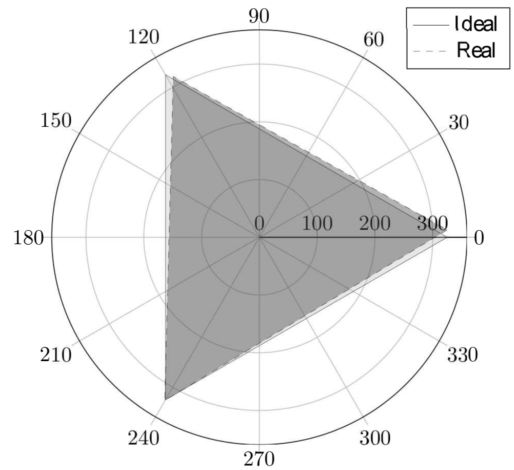
where Z_s is the symmetrical component mutual impedance matrix, and $\alpha = e^{j\frac{2}{3}\pi}$. If there are both negative and zero sequence symmetrical components present on the network, the dominant part of the voltage drop's negative and zero sequence can be calculated as follows (7).

$$\begin{aligned} \Delta U_2 &\approx Z_{21} I_1 + Z_{22} I_2 \\ \Delta U_0 &\approx Z_{01} I_1 + Z_{00} I_0, \end{aligned} \tag{7}$$

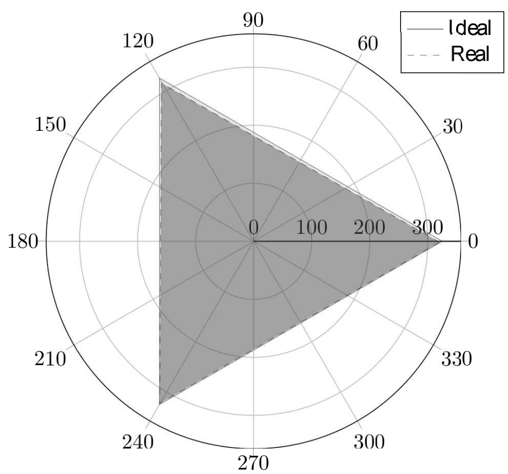
ΔU_0, ΔU_1, ΔU_2 are the voltage drop's zero positive and negative sequence components, I_0, I_1, I_2 are the current's drop's zero positive and negative sequence components, and Z_{00}, Z_{01}, Z_{21}, Z_{22} are mutual impedances, respectively. (If there is only positive and negative sequence present, then the right hand side's second term is zero.) As such, the indication of negative and zero



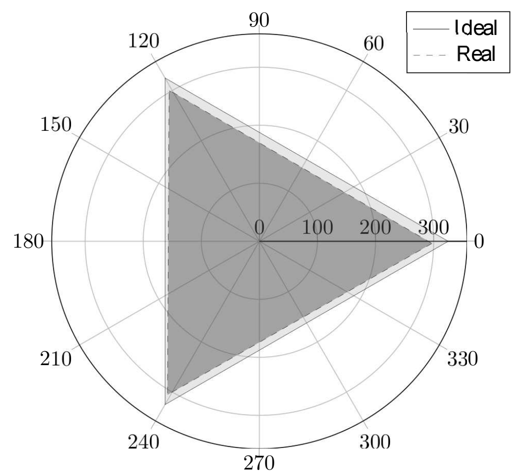
(a) High correlation with phase deviation. The norm values are $G = 3986$ and $TDV = 1.434$.



(b) High correlation with opposed amplitude deviation. The norm values are $G = 4198$ and $TDV = 1.612$.



(c) Low correlation with opposed amplitude deviation. The norm values are $G = 9322$ and $TDV = 0.5198$.



(d) Low correlation with uniform voltage drop. The norm values are $G = 6280$ and $TDV = 0.156$.

Figure 5: Four distinct cases of voltage triangles examining correlation between the regular TDV and geometrical G method.

sequence present the network calculates (8):

$$\begin{aligned} m_{21} &= \mid \tfrac{Z_{21}}{Z_{11}} \mid \times 100 \\ m_{01} &= \mid \tfrac{Z_{01}}{Z_{11}} \mid \times 100, \end{aligned} \tag{8}$$

where m_{21} is the negative sequence factor which is identical to the TDV (4), and m_{01} is the zero sequence factor.

At the previously described balanced over- or under-voltage case the positive sequence value is dominant, so the regular indicator will take considerably lower value. In other words, aside from indicating voltage unbalance, the geometrical method incorporates the balanced deviations as well. In a control design perspective, a general case, where notably highly unbalance values may appear, using TDV as cost function could introduce hidden errors in control due error cancellation. Additionally the geometrical solution checks electrical asymmetry, i.e. the norm of a ±120 degree rotated version of the ideal three-phase phasor is zero in the geometrical sense. Moreover, the geometrical norm is more sensitive for small scale unbalance, as opposed to the TDV. To summarise, the geometrical indicator a more suitable solution for a more general case indicator, and a good candidate for cost function in optimal control design.

3. Unbalance compensation

Based on the proposed measures of voltage unbalance it is possible to formulate some power quality related aims, or demands for the domestic size generator units as follows.

3.1. Problem statement

The voltage and current unbalance presents in the three phase low voltage transformer area causes additional power loss inside the medium voltage/low voltage transformer and in the transportation line wires too. It also has undesired effects in certain three phase loads, mainly rotating machines where it causes torque reduction and pulsating torque effect. Large scale unbalance can activate automatic protection functions of electricity dispatch system causes power outage. This is unpleasant for the customers and adds maintenance cost to the service provider. These negative effects lower the electric power quality and rises the cost of electrical energy and rises the carbon footprint of our everyday life. The paper's aim to propose a model and control for a three phase instrumentation, which can compensate these undesirable effects, lower or eliminate the voltage and current unbalance to lower the power losses and the CO_2 emission and increase power quality not only at the connection point but in the whole low voltage transformer area. It is important to note, that this power quality improvement can be achieved without any significant added cost. The future aim is to integrate this function into an existing three phase photovoltaic inverter device connected to the low voltage grid, and a complex energetic system is able to inject the renewable energy to the transportation network, can store the electrical energy from stochastic renewable sources in electrical vehicle batteries or feed the grid from the charged batteries in energy deficit and high demand simultaneous situations. Our new added value is the integrated control algorithm which can highly lower or eliminate the observed unbalance of the network.

3.2. Control problem

The above problem statement partially specifies the solution space together with the solution method. The system of interest is the power grid with all the stochastic and nonlinear phenomena present in it. The input to the system are current signals (one current in the single phase case and three in the three phase setup), which are naturally constrained by the available energy of the household - stored in a battery pack or momentarily generated by the wind or solar generator unit. The response of the system can be either the current or the voltage measured at the connection point of the inverter unit, however, the general legal regulations only allow voltage measurement for consumers. The difficulty of the control problem comes from the fact, that there are no mathematically tractable models of the network can be generated because of its unpredictable and nonlinear features. This means, that in these therms only black-box methods can be applied for this system.

For the control aim it is a natural choice to minimize the actual voltage unbalance of the low voltage local transformer area measured (or calculated) at the connection point of the inverter. Several optimization based methods are available for such kind of optimal control problems, e.g. Görbe et al. (2012) where the only bottleneck is the computational efficiency since the implemented controller has to run on the commercial inverter's hardware (digital signal processor unit).

3.3. Asymmetrical inverter structure

For the sake of completeness an asymmetrical inverter was developed in simulation environment, which is capable of carrying out the specified control task. The renewable energy injection is realized increasingly, and applied directly to the three phase low voltage grid with a domestic size photovoltaic power plant as source of power. This can reduce the voltage and current unbalance caused by the stochastic power production of wind and solar sources. More and more manufacturers produce three phase grid synchronized inverters from 5 kW size. These equipments implement accurate symmetrical current feed with a standard three phase full bridge structure, consists of six Isolated Gate Bipolar Transistors (IGBT). This is a cost effective standard structure suitable for symmetric harmonic current injection. It has limited capacities to inject not totally symmetric 3 phase current time functions, but Kirchhoff's current law permits only constant zero-sum current time functions injected with this structure. There are examples with this type of asymmetric current injections in the literature Lee et al. (2010).

This type of current injections has limited compensation capacity and this is not enough in most asymmetric production and load cases. In our case we need more general, not specific asymmetric current waveforms, because the proposed control aim assumes the ability of injecting non zero-sum currents. This needs special inverter design structure. We need zero line connection for the differential current. One of the possible solution is to use 3 different full bridge single phase current inverters to supply each phase of low voltage transportation lines Patnaik et al. (2013). But in this case we galvanic isolations are needed for these single phase inverters on the output, or on the DC input size.

This isolation can be reached with using isolation transformers in the supply side. But we prefer to use it a complex energetic system with specific inside true DC bus system feeded from Photovoltaic panel or batteries. We have to isolate at least 2 full bridges with two way DC-DC converters. This can complicate the physical realization but easy to simulate with two controlled power source. Other possible easy to realize solution to isolate the full bridge outputs connected to three phase lines with isolating transformers. It is recommended due to electric shock protection reasons. Our distant aim to compensate other operational type line failures, such zero current appearing. This isolation method doesn't allow to produce DC current components, thats why we are looking for other design. Possible elegant solution to supplement the standard three phase inverter design with a fourth half bridge for Zero line, building a specific four leg inverter design Ninad et al. (2014).

Only drawback of this solution is the complex difficult control method of the half bridges, to keep the current sum in zero values in each moment, and to provide the correct current paths inside the inverter. This structure has the lowest production cost, but in the phase of proofing the asymmetry compensation we chose the DC-DC isolated full bridge design for simulation purpose because of the simple control during simulation.

As a further generalization step, the injection of no harmonic current shapes will be necessary in order to decrease the extant Total Harmonic Distortion (THD) of the network. These expectations yield an inverter with new structure suitable for arbitrary current injections without limitations. The design lends similar elements like in Görbe et al. (2012) by means of battery charge, renewable power point tracking, intermediate voltage, and IGBT bridge control, but in this case the problem requires a three phase solution for the voltage unbalance reduction. The applied structure based on a full bridge IGBT structure used in single phase current injection. Three different IGBT full bridge were connected at the output point, thus our structure has three phase and neutral connection too, to carry out any current form. The disadvantage of this structure is that it needs 12 IGBTs in the output stage as opposed to the 6 IGBTs needed for a classical full bridge structure and needs three galvanically isolated direct current (DC) voltage source for feeding. The other standard elements, that the inverter design consists:

- Standard maximum power point tracking (MPPT) input stage, to inject the maximum available power from the renewable source to the intermediate voltage capacitor with a simple controlled boost converter
- A half bridge current controller to charge or deploy the battery pack connected to the complex energetic system for energy storage and energy unbalance compensation
- Intermediate voltage controller
- Universal three phase output stage with 3 single phase full bridge IGBT current injector and 2 high current DC-DC converter

This is suitable to inject any necessary current shape to the low voltage three phase grid connection even DC currents too. Later a power loss and production cost analysis will be necessary if the built structure will be suitable for asymmetric compensation of low voltage transformer area.

Of course there is a possibility that there is no renewable power available for a longer period of time and the battery completely looses its charge. In this case the system should work merely with the power of the connection

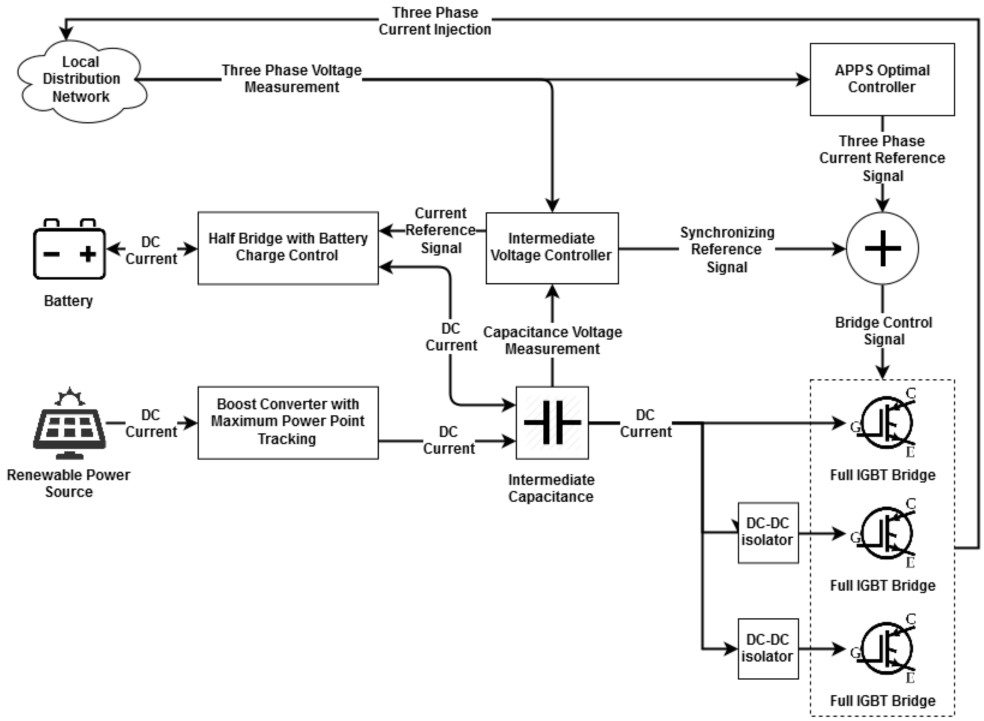


Figure 6: The asymmetrical inverter design, which applies three single phase full bridge IGBT current injector to create the injected asymmetrical current shapes for voltage unbalance compensation.

point but with zero energy balance. This states to operate two controller with semi-opposite control goals. The optimization based controller requires current injection while the intermediate voltage controller (Figure 6) keeps the inverters energy balance. Although for this operation some of the control's performance should be sacrificed, unbalance compensation could be achieved even without external renewable power, and energy storage at a minimum power requirement.

3.3.1. Measurements from a real unbalanced network

The measurements took place at the Faculty's building, where a common 400 V connection point was investigated as the behaviour of the network. The three phase 230 V line-to-ground voltages has been transformed to 6 V to be effectively measurable time domain with high performance NI-USB DAQ on 10 ksample/s. Because of the limited computational capacity only a 10 second measurement was made in every hour. The measurements then has been merged and smoothed to eliminate the inter-measurement transients. Afterwards, the measurement data has been used as the input of a micro-grid segment of the Matlab/Simulink model, to test the controller and inverters structure's performance in quasi-realistic circumstances. The controllers performance on the simulated microgrid's network loss reduction can be observed on Figure 11 and Figure 12. The measurement output is connected to a modeled three phase load and network system, consisting of symmetrical loads and network segments between them. Further artificial load unbalance is not necessary since the network's unbalance is already present. This structure enables to show that any point the inverter is connected could serve as quality restoration such unbalance compensation at this case. Our future plan is to set up multiple devices on different connection points.

3.4. Optimization based control algorithm

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 (APPS) which could be able to control our scenario. We applied a vari-

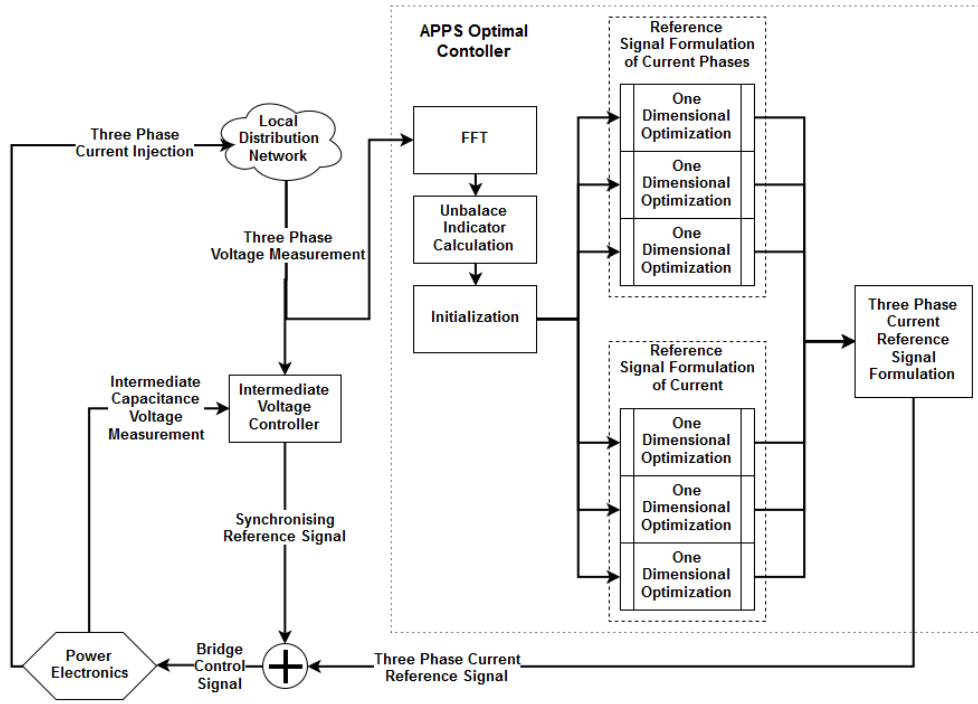


Figure 7: The optimization algorithm implemented for current control. A one dimensional linear optimization step is being solved in each dimension of the six dimensional parameter space, iteratively.

ant 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, ideally, converges to local multivariate extreme value $x(k)$ of the function (9).

$$\begin{aligned} x^{(k)} &= x^{(k-1)} - t_k \nabla f(x^{(k-1)}) \\ k &\in \mathbb{N} \end{aligned} \tag{9}$$

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 if $\Delta k > 0$, using (10).

$$\begin{aligned} x^{(k+1)} &= x^{(k)} + \Delta_k d_i \\ \text{if} \quad & f(x^{(k)} + \Delta_k d_i) \leq f(x^{(k)}) \\ k &\in \mathbb{N} \end{aligned} \tag{10}$$

The parameter is $x(k) \in R_n$, and the search pattern $p \in D = d_1, ...d_n$ 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 is not enough computing power available for direction vector p, synchronization should not be maintained. In this case we are talking about the asynchronous case . 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. 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.

Unlike other similar approaches, e.g. Segui-Chilet et al. (2013), the explained optimal controller does not rely on a measured current signal (which varies according where the measurement took place on the grid and renders the global optimisation unreliable) but rather measuring and analysing the voltage unbalance via the proposed indicator and optimizes the voltage shape, the latter of which depends on the nonlinear distortion of the whole low-voltage transformer area and determines additional power losses. The controller's performance was compared to a non compensated network, and a network consisting synchronised symmetric power intake from a regular inverter.

In each iteration only one physical value is changing on the six dimensional parameter field, which consists of the three amplitude and three phase values. If the change effects with cost function reduction (the reference norm's normalised value), the controller holds the new value of amplitude or phase for the controlled current sources (Figure 7). The advantage of this controller structure that is not necessary to know the controlled value's behaviour well, like we could not determine the number and type of the other loads on the network Neukirchner et al. (2015a). There are however two disadvantages. First is the low speed of control, due to the several necessary iterations (depending on the circumstances) to find the optimal directions in the parameter space, and the serial nature of interventions and norm calculations. The second comes from the method itself since the controller may stuck in local minima.

4. Discussion

4.1. Dynamical simulation based experiments

In order to be able to investigate the proposed optimization based unbalance reduction control structure with the three phase inverter on a low voltage local grid, all the elements of this complex electrical system (including the photovoltaic source, the inverter, the battery and the nonlinear local grid with different types of loads) has been modeled in Matlab/Simulink environment. The primary aim of the simulation based experiments were to serve as a proof of concept for the proposed complex control structure.

4.2. Performance analysis

The aim of performance analysis is twofold. First of all, the proposed voltage unbalance indicator has to be investigated in the control structure as the cost function of the optimization based controller, and on the other hand, the control structure itself has to be exposed against engineering expectations.

The results of the first experiment can be seen in Figure 8 where the geometrical norm 5 has been used as the voltage unbalance indicator and the cost function for the optimizer. The dashed line represents the examined low voltage local network's unbalance norm (G) without the proposed controller implemented in the inverter unit of the domestic powerplant while the solid line represents the compensated network's norm value. The performance of the controller with this norm is apparent, it was able to decrease the network voltage unbalance by approximately 85 %. In this experimental setup the controller has enough input energy due to the batteries and the available solar power.

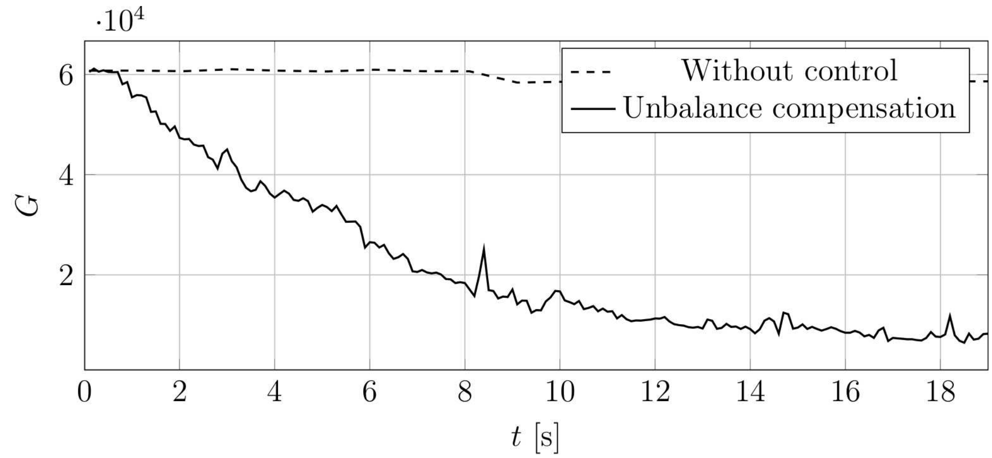


Figure 8: Unbalance reduction control system performance with half charged battery and photovoltaic power source available. The underlying unbalance norm is the geometrical one (G) in this experiment. After starting the controller at $t = 0.1s$ the unbalance measure G of the network significantly decrease.

A slightly more challenging situation is investigated in Figure 9 where the controller had had to operate without photovoltaic source and batteries. This is called zero balance operation mode when the energy obtained from the network is reinjected in such a way that the unbalance indicators decrease. It can be seen that the performance of the controller is modest than that of

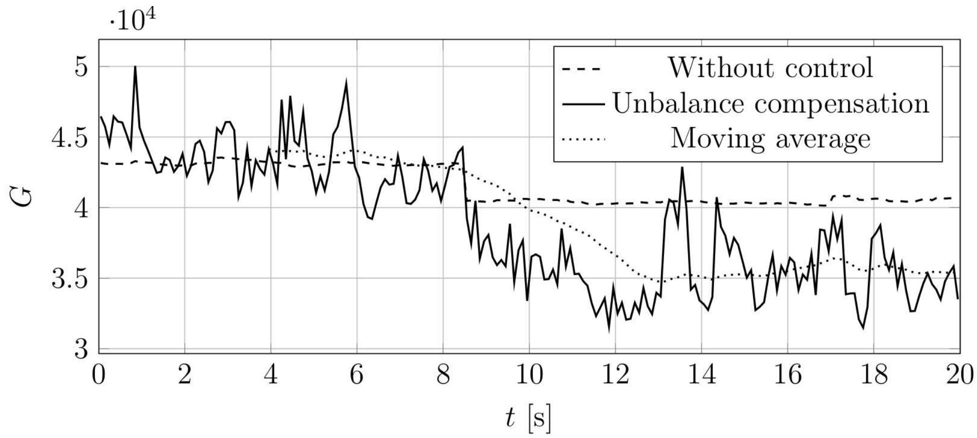


Figure 9: Unbalance reduction control system performance without battery and renewable source (zero energy balance operation). The performance reduction is clearly observable compared to the case when external power source is available (Figure 8), but as result the voltage unbalance indicator G reduced by the average value of 14.78%.

Figure 8, but it is still acceptable.

4.2.1. Robustness analysis

The robustness of the proposed control structure is an important qualitative property with respect to the time dependent loads present on the network. The robustness of the proposed controller had to be tested via simulation when different types of loads (inductive, capacitive, resistive) had been varied in step changes representing representing the on/off switching the different types of household appliances (motors, switching mode power supplies, electric heaters, etc.). In the experiment depicted in Figure 10, a load change has been introduced to the network in every 15 seconds causing the voltage unbalance to jump to a different value (measured in the geometrical norm (5)). As it can be seen in the figure the controller successfully compensates the unbalance after each transient.

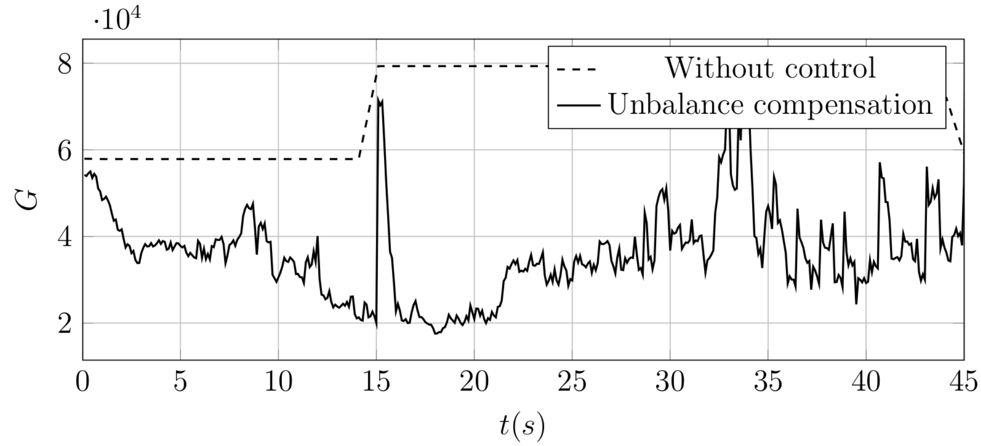


Figure 10: Robustness analysis with respect to step type changes in the network load (and voltage unbalance). The unbalance reduction controller successfully compensates the changes in the network voltage unbalance norm (G) value.

4.3. Environmental effect

The favorable effects of the proposed unbalance reduction control algorithm , i.e. increase power quality not only at the connection point but in the whole low voltage transformer area, which causes a reduction of the effective power loss and the reduction in the CO_2 emission.

4.3.1. Power loss reduction on the network

Network loss reduction due to the unbalance reduction compensation control is investigated on Figure 11 where the simulation experiment was carried out in the circumstance when the renewable source was not shut down (e.g. insufficient amount of sunlight) and additionally the battery was drained completely Neukirchner et al. (2015a), Neukirchner et al. (2015b).

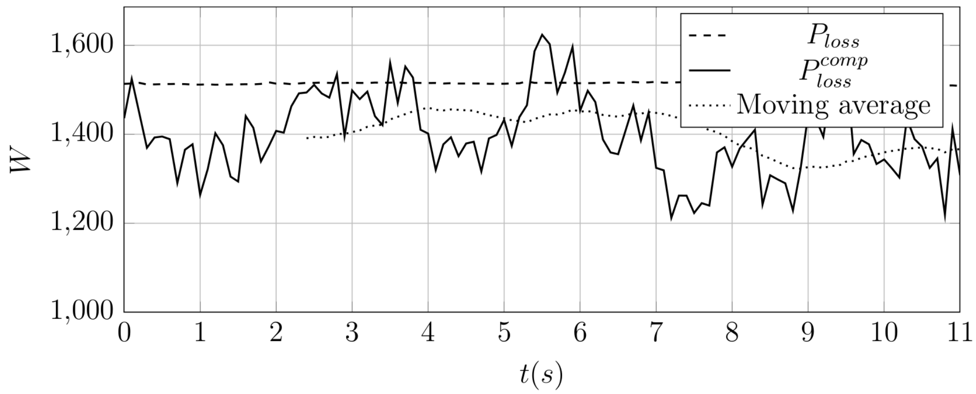


Figure 11: Compensation control's loss reduction during zero energy balance operation on the modeled network, where P_{loss} indicates the effective power losses and P_{loss}^{comp} effective power losses during control of the network. As result the network losses reduced by mean 6.5%.

The results show that despite of the negative cross effects of the intermediate voltage controller and the unbalance reduction controller it was possible to find the trade-off between the control goals of the different controllers (maintain zero energy balance for the inverter and decrease the unbalance on the network). The estimated loss reduction in the experimental setup is 6.5%.

4.3.2. CO_2 footprint

The fact that this controller enables the reactive power reduction has a favourable consequence, i.e. the power loss or equivalently CO_2 emission and the carbon footprint can also be decreased. The estimated environmental effects of voltage asymmetry compensation can be calculated. Let us assume 3000 kWh for the yearly electric energy consumption an average household and 9.173% for the loss of the distribution network MVM (2013). With

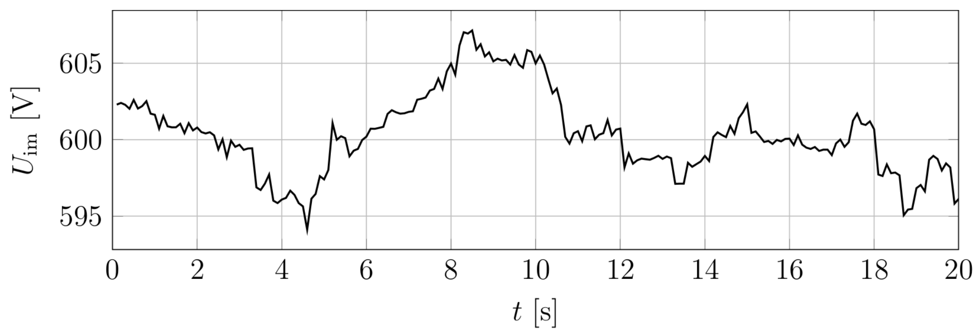


Figure 12: Intermediate puffer capacitance's voltage within boundaries (600±10 V), during zero energy balance operation mode of the voltage unbalance compensation controller. U_{im} indicates intermediate the capacitance's voltage.

the controller the losses on the simulated network are reduced by 6.5%. The calculation follows (11)

$$\begin{aligned} P_{loss} &= 3000\,\mathrm{kWh} \cdot 9.173\% \\ P_{loss}^{comp} &= 3000\,\mathrm{kWh} \cdot (9.173 \cdot 0.93)\% \\ \Delta P_{loss} &= P_{loss} - P_{loss}^{comp} \end{aligned} \tag{11}$$

where P_{loss} is the assumed network loss per household and P_{loss}^{comp} is s the assumed network loss with unbalance compensation control and ΔP_{loss} is the saved energy. According to (11), unbalance compensation results in an energy savings of 19.26 kWh. Taking into account the proportion of power currently generated by fossil fuels (coal 17.3 %, gas 38.3% MVM (2013), Görbe et al. (2012)) and the rate of CO_2 emission during electric energy production (1,000 g/kWh from coal and 430 g/kWh from gas), it can be concluded that voltage unbalance compensation could reduce CO_2 emissions by 6504.9 g a year, in an average household.

5. Conclusion

The defined norm is applied as a cost function in the asymmetry reducing controller structure also presented in the paper. Simulations show that the geometrical based indicator can serve as a basis of further research. The suggested controller structure enables the residential users owning a grid synchronized domestic power plant to reduce voltage unbalance measurable at the connection point. The fundamental element of the system is a modified three phase inverter that is capable of the asymmetric injection of any current waveforms to the network. The optimization based control algorithm injects the available energy (as current waveform) in such a way, that the voltage unbalance decreases. This optimization problem is usually constrained by the available renewable energy supplied by the power plant.

The control structure has been tested on a low voltage network model in a dynamical simulation environment consisting of the models of the electrical grid, a domestic power plant, asymmetrical inverter circuit, and different types of loads. Different simulation experiments has been run for each norm and for both the power constrained and unconstrained case. The preliminary results show that this structure can serve as a residential level voltage quality improvement method for the three phase low voltage network also indirectly reduces the CO_2 emission due facilitating more effective energy usage.

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