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Reference Signal Generators for Distributed Compensation

***Abstract**. Various methods are used to generate the control reference signals for power electronics based compensators in three-phase distribution systems. In cases where increased flexibility and sharing duties across multiple compensators provides a cost benefit, the applicability of reference signal generation methods for distributed compensation applications should be evaluated. Shared compensation requires an understanding of power components that are present to enable priority based decisions with respect to the sharing. This paper provides an overview of several reference signal generation methods for power electronic converters when used in a cooperative fashion for sharing compensation duties within an electrical grid.*

Streszczenie.** Wiele różnych metod stosuje się dla generowania sygnałów sterowania kompensatorów energoelektronicznych w systemach rozdzielczych. W sytuacjach, w których rosnąca elestyczność i podział zadań kompensatorów rozproszonych daje korzyści finansowe, sterowanie takich kompensatorów jest ważnym przedmiotem zainteresowania. Kompensacja rozproszona wymaga opisu energetycznego systemu, umożliwiającego podział ról kompensatorów. Niniejszy artykuł przedstawia przegląd metod generowania sygnalów sterujących kompensatorów rozproszonych.(**Porównanie przydatności różnych teorii mocy do sterowania kompensatorów kluczujących)

Keywords: voltage-source converters, active compensator, active filters, distributed compensation, microgrid.
Słowa kluczowe: Konwertery ze źrółem napięciowym, kompensatory aktywne, filtry aktywne, kompensacja rozproszona, mikro-sieci

Introduction

The subject of components not associated with active power, sometimes referred to as useless components, and their compensation has long been a topic of discussion among researchers. In addition, increasing use of power electronics in power systems as well as in microgrids provides opportunities for distributed compensation if those power electronics have flexibility to allow for various compensation functions as well as their coordination to achieve the overall compensation objectives. Thus, there have been recent trends toward multi-functionality of power electronic converters combining compensation with other functions or requiring flexible compensation. For example, it may be desirable to perform compensation with converters used for interfacing of renewable sources during time intervals that they are not fully utilized for renewable genererated energy transfer. Also, non-ideal supply conditions are warranting more attention as weak grids such as microgrid systems are gaining interest. With increased flexibility requirements and the need to share duties across multiple compensators, the applicability of reference signal generation methods for distributed compensation applications should be evaluated.

Various methods are used to generate the control reference signals for power electronics based compensation systems. These systems, when harmonic compensation is included, are usually referred to as active filters, active power filters or active harmonic filters. In some cases compensation objectives may not include harmonics and the more general term active compensator is used to indicate that any component or group of components of the current may be compensated. Such power electronics based compensators are referred to in this paper as switching compensators as in [1] since they rely on semiconductor switching in order to compensate for some undesirable components of current or voltage in a system.

This paper provides an overview of several methods for the generation of reference signals used in control of power electronic converters that must share compensation duties with other devices.

Power electronic converter based compensators

Power electronic converters used in compensation applications can be grouped into one of three broad categories: shunt connected current compensators, series connected voltage compensators, and combinations thereof. The shunt connected current compensator is the most prevalent and will be the focus of compensation examples in this paper. Figure 1 depicts a generalized voltage source converter (VSC) based current compensator with the control functions partitioned into several hierarchical layers.

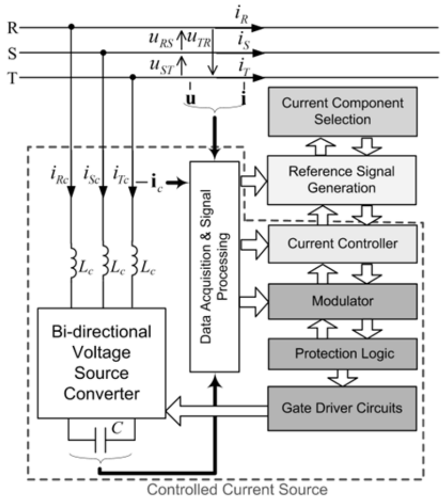

Figure 1. Functional diagram of a generalized three-phase Voltage Source Converter.

The control layers can be grouped into two main parts. The first is the current controller [2] and lower level controls that cause the power electronics hardware to behave as a controlled current source, as depicted by the dashed line. The power electronic equipment and control sub-systems within the dashed line act as a controlled source.

The second part is the reference signal generator that generates the current reference signal for the controlled current source according to the mission of the particular shunt connected VSC. Thus, an appropriate reference signal generator can enable the VSC to operate as a compensator by extracting the desired components of the current in an appropriate manner [3-11]. It will also include a voltage reference sub-system when the VSC operates as a isolated microgrid supply. A higher level or system control may or may not be present. In the general control structure considered here a higher level control is assumed that selects the particular current components present in the AC lines of the VSC and determines how duties are distributed among multiple compensators.

Types of Distributed Compensation

In the broadest sense distributed compensation means utilization of two or more power electronic devices with compensation functions that are coordinated in order to achieve an overall compensation objective. Two main types are distributed grid connected compensators and distributed isolated microgrid compensators. In addition they may be co-located compensators or network distributed compensators.

a. Co-located compensators

Co-located compensators are connected at the same cross section of the distribution system as shown in Fig 2. This configuration is used when it is not desirable to utilize a single compensator to generate all compensating current components. Current components at the fundamental frequency are typically much larger than harmonic components. Therefore, low frequency switching power electronic converters may be used for the lower frequency components of the current while high frequency switching converters with lower rating may be used for high frequency component compensation. Some compensators for fundamental frequency components may generate harmonic components if they are composed of thyristor based circuits. In that case the high frequency compensator should be located on the source side of the thyristor based compensator in order to eliminate compensator generated as well as load generated harmonics. Also, larger capacity energy storage may be required for some compensation goals if active current is needed.

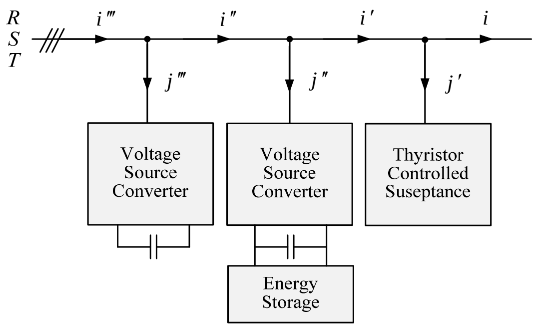

Figure 2. Co-located grid connected compensators

b. Distributed grid connected compensators

Distributed grid connected compensators are connected at different distribution system busses as depicted in Fig 3. In this configuration the main grid is the source of voltage and each compensator operates as a controlled current source. A control method is needed to determine sharing of the current components injected or drawn by the compensators.

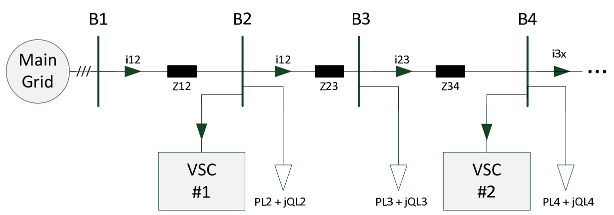

Figure 3. Distribtuted grid connected compensators

c. Distributed isolated microgrid compensators

Distributed isolated microgrid compensators are connected at different distribution system buses as depicted in Fig 4. In this configuration the converters are not only compensators but also they are the supplies and provide the source of voltage. In this configuration compensation means that each converter shares non-active currents required by the loads in such a way that voltage at the load bus is maintained according to a desired power quality target.

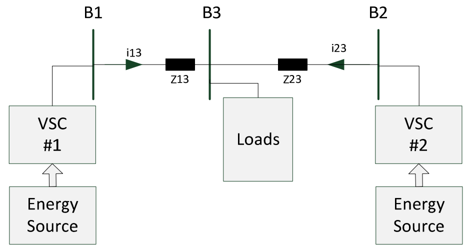

Figure 4. Distributed isolated microgrid compensators

Compensation objectives

The desired form of compensation depends upon the objectives. Some common objectives are:

1. Source current should have a minimum RMS value
2. Source current should be sinusoidal and may also be required to have a particular phase and degree of symmetry
3. Bus voltage should be sinusoidal and may also be required to have a particular degree of symmetry
4. Instantaneous active power at the supply should be constant

Here both voltage and current are considered to be distorted and asymmetrical. The currents and voltages measured with respect to an artificial zero may be expressed in vector form as

$$u = \sum_{n\in N} \begin{bmatrix} u_{Rn} \\ u_{Sn} \\ u_{Tn} \end{bmatrix} \qquad i = \sum_{n\in N} \begin{bmatrix} i_{Rn} \\ i_{Sn} \\ i_{Tn} \end{bmatrix}, \tag{1}$$

where N is the set of voltage and current harmonics including the fundamental.

$$u = u_1^P + u_1^N + u_h \tag{2}$$

where $\boldsymbol{u}_1^P$ is the fundamental positive sequence sinusoidal voltage vector, $\boldsymbol{u}_1^N$ is the fundamental negative sequence sinusoidal voltage vector and $\boldsymbol{u}_h$ is the distored component of the voltage. Under the condition that the supply voltage is non-sinusoidal and/or asymmetrical the compensation goals cannot be simultaneously met. The tradeoff between various compensation options are best described in the frequency domain.

The CPC theory developed in the frequency domain by Czarnecki [14-16] is based on orthogonal decomposition of the current. For each harmonic the theory decomposes the current into active, scattered, reactive and unbalanced components. In order to perform this decomposition the load is expressed in terms of two admittances for any harmonic frequency, the equivalent admittance and the unbalanced admittance. The equivalent admittance of the fundamental is expressed as

$$\boldsymbol{Y}_{e1} = G_{e1} + jB_{e1} = \boldsymbol{Y}_{RS1} + \boldsymbol{Y}_{ST1} + \boldsymbol{Y}_{TR1}, \tag{3}$$

where G_{e1} and B_{e1} are the equivalent conductance and equivalent susceptance respectively. The unbalanced positive sequence admittance of the fundamental is

(4) $$A_1^P = A_1^P e^{j\varphi_1} = -(Y_{ST1} + \alpha Y_{TR1} + \alpha^* Y_{RS1}),$$

relating components of the unbalanced load current to the supply positive sequence voltage and unbalanced negative sequence admittance is

(5) $$A_1^N = A_1^N e^{j\varphi_1} = -(Y_{ST1} + \alpha^* Y_{TR1} + \alpha Y_{RS1}),$$

relating components of the unbalanced load current to the supply negative sequence voltage where $\alpha = 1e^{j120°}$ and $\alpha^* = 1e^{-j120°}$. In the case of asymmetrical supply voltage and unbalanced load an additional equivalent admittance referred to as the asymmetry dependent admittance [15] has a non-zero value equal to

(6) $$Y_{d1} = G_{d1} + jB_{d1} = Y_{e1} - \frac{3}{\|u\|^2}\left(Y_{ST1}U_{R1}^2 + Y_{TR1}U_{S1}^2 + Y_{RS1}U_{T1}^2\right).$$

Assuming that the supply voltage is symmetrical then Y_{d1} is zero and the three-phase current vector of the fundamental can be decomposed into mutually orthogonal components as

(7) $$i = i_a + i_{r1} + i_{s1} + i_{u1} + i_h,$$

where i_a is the active component of the current and the fundamental active component of the current is

(8) $$i_{a1} = \sqrt{2}\,\mathrm{Re}\left\{G_{e1}\left[U_{R1} \quad U_{S1} \quad U_{T1}\right]^{\mathrm{T}} e^{j\omega_1 t}\right\},$$

the fundamental reactive component of the current is

(9) $$i_{r1} = \sqrt{2}\,\mathrm{Re}\left\{jB_{e1}\left[U_{R1} \quad U_{S1} \quad U_{T1}\right]^{\mathrm{T}} e^{j\omega_1 t}\right\},$$

and the fundamental unbalanced component of the current is

(10) $$i_{u1} = \sqrt{2}\,\mathrm{Re}\left\{A_1^P\left[U_{R1} \quad U_{T1} \quad U_{S1}\right]^{\mathrm{T}} e^{j\omega_1 t}\right\}$$

i_h is the lumped harmonic components of the current and i_{s1} is the fundamental component of the scattered current equal to

(11) $$i_{s1} = \sqrt{2}\,\mathrm{Re}\left\{(G_{e1} - G_e)\left[U_{R1} \quad U_{S1} \quad U_{T1}\right]^{\mathrm{T}} e^{j\omega_1 t}\right\}.$$

A compensating current can be based on this decomposition. If only the current components at the fundamental are computed then the compensating current is expressed as

(12) $$j = i_{r1} + i_{u1} + i_h = i_{r1} + i_{u1} + i - (i_{a1} + i_{r1} + i_{u1}),$$

where the harmonic components of the current are determined by subtracting the fundamental components. In this case the supply current after compensation is equal to

(13) $$i' = i - j = i_{a1} = i_a + \sum_{n\in N} i_{sn} - \sum_{n\in N_h} i_{an},$$

where N_h denotes the set of orders n without the fundamental. Only the equivalent conductance of the fundamental is computed and not the equivalent conductance. Therefore, if voltage distortion is not reduced to zero by the compensation of the harmonic components of the current then the supply current RMS value will always be higher than its minimum. However, the supply current will be sinusoidal. If the scattered currents are computed then the supply current RMS value can be minimized, however, some distortion will remain since the active current i_a is not sinusoidal.

Although compensating all useless components of the current is ideal, it is often desirable to target a sub-set of the possible components of the current due to power electronic converter power and switching speed limitations, etc. Furthermore, the compensation objectives may vary over time. An example of a switching compensator reference signal [10] for variable compensation objectives and sinusoidal supply current is the linear form

(14) $$j^* = K_a i_{a1} + K_r i_{r1} + K_u i_{u1} + K_h i_h + i_c$$

where K_a, K_r, K_u and K_h are scaling coefficients of the active, reactive, unbalanced and harmonic components respectively. The final term in the expression is the switching compensator active power which is needed to active maintain power balance as well as to supply power to the compensator due to losses. Depending on the compensation goals and power components present in the system the compensator active current may also consist of active power at harmonic frequencies or negative sequence.

In the case that the supply voltage is asymmetrical then the fundamental unbalanced current is composed of both positive and negative sequence components

(15) $$i_{u1}^P = \sqrt{2}\,\mathrm{Re}\left\{\begin{pmatrix} A_1^P\left[U_{R1}^P \quad U_{T1}^P \quad U_{S1}^P\right]^{\mathrm{T}} - \\ Y_{d1}\left[U_{R1}^P \quad U_{S1}^P \quad U_{T1}^P\right]^{\mathrm{T}} \end{pmatrix} e^{j\omega_1 t}\right\}$$

and

(16) $$i_{u1}^N = \sqrt{2}\,\mathrm{Re}\left\{\begin{pmatrix} A_1^N\left[U_{R1}^N \quad U_{T1}^N \quad U_{S1}^N\right]^{\mathrm{T}} - \\ Y_{d1}\left[U_{R1}^N \quad U_{S1}^N \quad U_{T1}^N\right]^{\mathrm{T}} \end{pmatrix} e^{j\omega_1 t}\right\},$$

where the asymmetry dependent admittance, Y_{d1}, removes the portion of opposite sequence current that occurs due to supply asymmetry for the balanced equivalent load.

The reference signal will take on different forms depending on the goals of compensation and whether it is expressed in the time domain, frequency domain or both.

Generation of reference signals

Whether a reference signal generation method is based on a time-domain or frequency domain approach, the basic elements are the same. Power or current components present at a measurement point are determined followed by extraction of selected subsets of those components. Finally, a compensation command signal is constructed from the selected subset.

Compensator control in the frequency domain based on (14) can be achieved in either the synchronous or stationary reference frames. In either case an efficient recursive discrete Fourier Transform (RDFT) algorithm [10-11] for computing components of the measured quantities and a current decomposition algorithm used to provide separate control of orthogonal current components is required.

In the case that the supply is asymmetrical, voltage sequence must be separated in order for the unbalanced current in (7) to have meaning. In order for the converter to inject or draw balanced currents, only positive-sequence voltage is used by the reference signal generator. To extract the positive sequence component the RDFT can be taken for each phase quantity with respect to the axis of that phase so that real and imaginary parts are equal to

$$\begin{aligned}\mathrm{Re}\{\tilde{\boldsymbol{X}}_{1,k}\} &= \mathrm{Re}\{\tilde{\boldsymbol{X}}_{1,k-1}\} + x_k C_k - x_{k-N} C_k \\ \mathrm{Im}\{\tilde{\boldsymbol{X}}_{1,k}\} &= \mathrm{Im}\{\tilde{\boldsymbol{X}}_{1,k-1}\} - x_k S_k + x_{k-N} S_k\end{aligned} \tag{17}$$

where C_k and S_k for each phase are given by

$$\begin{bmatrix} C_{kR} & C_{kS} & C_{kT} \end{bmatrix}^{\mathrm{T}} = \cos(\omega_{1g} k + \boldsymbol{\beta}) \tag{18}$$

$$\begin{bmatrix} S_{kR} & S_{kS} & S_{kT} \end{bmatrix}^{\mathrm{T}} = \sin(\omega_{1g} k + \boldsymbol{\beta}) \tag{19}$$

and

$$\boldsymbol{\beta} = \frac{2\pi}{3}\begin{bmatrix} 0 & -1 & 1 \end{bmatrix}^{\mathrm{T}}. \tag{20}$$

Outputs of the RDFT with respect to this modified reference system are denoted by with a superscript *β*. Then the CRMS value of the positive sequence component of the supply voltage fundamental is given by

$$\mathrm{Re}\{U^P\} = \frac{1}{3}\left[\mathrm{Re}\{\tilde{U}_R\}^{\beta} + \mathrm{Re}\{\tilde{U}_S\}^{\beta} + \mathrm{Re}\{\tilde{U}_T\}^{\beta}\right] \tag{21}$$

$$\mathrm{Im}\{U^P\} = \frac{1}{3}\left[\mathrm{Im}\{\tilde{U}_R\}^{\beta} + \mathrm{Im}\{\tilde{U}_S\}^{\beta} + \mathrm{Im}\{\tilde{U}_T\}^{\beta}\right]. \tag{22}$$

This is similar to the approach given in [12] except that there a recursive bandpass filter is used to extract the fundamental. Simply changing the sign of the terms in (20) will yield the negative sequence component.

Calculating the CRMS values of the measured voltages and currents using a RDFT their ratio can be interpreted as admittances for the fundamental frequency. The value of these admittances can change as the RDFT moving window advances. Therefore, the admittances are considered as time varying quantities and the two necessary admittances are referred to as *time varying admittances of an equivalent load*. They are calculated by

$$\tilde{\boldsymbol{Y}}_{TR} = \frac{\tilde{I}_R}{\tilde{U}_{RT}}, \quad \tilde{\boldsymbol{Y}}_{ST} = \frac{\tilde{I}_S}{\tilde{U}_{ST}}. \tag{23}$$

Having these two admittances the *time varying equivalent admittance* is given by

$$\tilde{\boldsymbol{Y}}_e = \tilde{G}_e + j\tilde{B}_e = \tilde{\boldsymbol{Y}}_{ST} + \tilde{\boldsymbol{Y}}_{TR} \tag{24}$$

and the *time varying unbalanced admittance* positive sequence component is given by

$$\tilde{\boldsymbol{A}}^P = \left|\tilde{\boldsymbol{A}}^P\right| e^{j\tilde{\varphi}^P} = -(\tilde{\boldsymbol{Y}}_{ST} + \alpha\tilde{\boldsymbol{Y}}_{TR}), \tag{25}$$

etc. In this manner any needed time varying versions of the fictitious admittances needed for decomposition of current components can be generated.

a. references for grid connected compensators

Grid connected compensators whether co-located or distributed connected as shown in Fig. 2 and Fig. 3 act as current sources. Their main difference is in the method for determining how duties are shared among the compensators.

For co-located compensators in order to provide flexibility of the compensation objectives among the compensators the current control reference signal for each one can be expressed as the linear form given in (14). Since the compensators are co-located a central control can determine sharing among each by setting the scaling coefficients.

In the case that the supply is asymmetrical, voltage sequence must be separated in order for unbalanced current to have meaning. If the compensation goal is sinusoidal balanced current on the supply side of the compensator, only positive-sequence voltage is used by the reference signal generator. Thus, active component of the converter, i_{Ca}, is equal to

$$i_{Ca} = \frac{\Delta P_{sc} + \left\|i_{a1}^N\right\|\left\|u_1^N\right\| + \sum_{n\in N_h}\left\|i_{an}\right\|\left\|u_n\right\|}{\left\|u_1^P\right\|^2} u_1^P \tag{26}$$

where ΔP_{sc} are losses of the converter. Superscripts '*P*' and '*N*' denote positive and negative sequences respectively. Active component of the converter is adjusted by the DC bus voltage control as needed to satisfy the power balance.

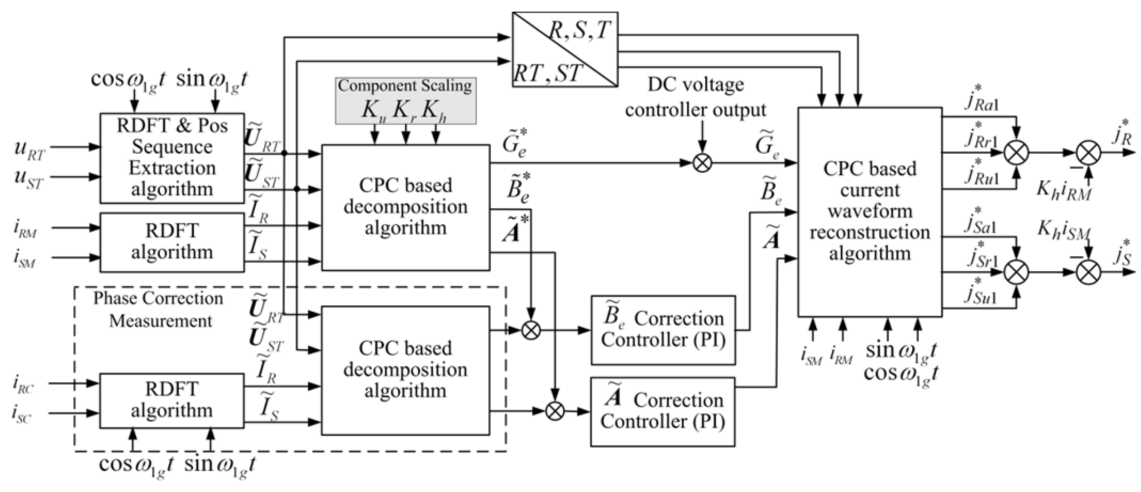

Figure 5. General current reference signal generator in the stationary reference frame.

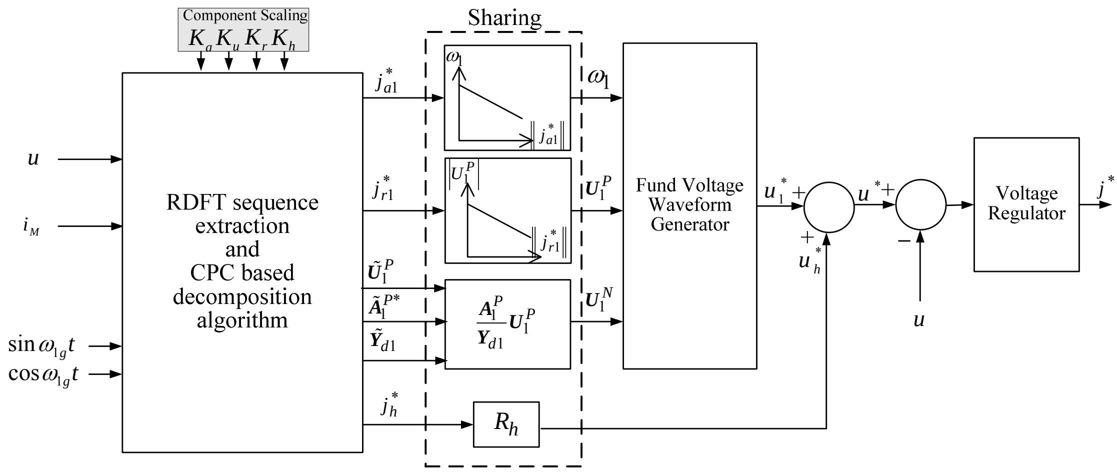

Figure 6. Reference signal generator for stand alone microgrid operation with current sharing control.

A simplified block diagram of a CPC reference signal generation strategy to realize (14) is shown in Fig. 5. The main feature of this architecture is the RDFT and orthogonal current decomposition that provides the current reference signals. The reference signal generator is comprised of several parts: the RDFT measurement and decomposition algorithm used for measuring the necessary voltages and currents and decomposing them into equivalent and unbalanced admittances, and the current waveform reconstruction algorithm that transforms the frequency-domain references back to time-domain current waveforms. In addition to these there are two feedback control loops associated with the reference signal generation. These are current controllers that ensure the reactive and unbalanced currents are equal to the set-point in the presence of any RDFT induced phase error. The RDFT calculation of the measured voltage can contain a phase error due to lack of synchronization of the RDFT with the fundamental [17].

The same reference signal generator can be used for distributed grid connected compensators with the exception of how the current component scaling coefficients are used for sharing allocation. Communication based approaches to distributed compensation are described in [18] where information based on local converter measurements must be communicated in order to determine sharing coefficient settings. Often droop based approaches are used to accomplish sharing when communication links are not preferred [19-22].

b. references for isolated microgrid compensators

Converters used in isolated microgrids must act as the source of voltage when disconnected from the main grid. Therefore, they act as voltage sources and a voltage generator section must be added to the reference signal generator. The converters can still be viewed as compensators since in general various components of current supplied by the converters should be shared in such a way that the power quality at load busses is maintained [20]. A coordinating control section is added to the CPC based reference generator shown in Fig. 5 along with a voltage regulator as shown in Fig. 6. The RDFT and CPC decompositions sections are the same except that only the converter current needs to be measured in this case.

Coordinated control of active and reactive current is performed by the use of current based droop control. Similar to active and reactive power based droop control current based droop can be given as

(27) $$\omega = \omega_o - s_\omega \left\| j_{a1}^* \right\|$$

(28) $$U_1^P = U_o - s_u \left\| j_{r1}^* \right\| .$$

In these equations ω_0 and U_0 are the rated values of frequency and voltage magnitude while s_ω and s_u are slopes of droop characteristic lines which are determined based on the ratio of active and reactive current sharing and with consideration of frequency and voltage limits.

Harmonic current sharing the harmonic component of the current, which is extracted based on CPC power theory, is multiplied by a harmonic resistance. This can be seen as a droop characteristic line for harmonic sharing. The slope of this characteristic is inversely proportional to the amount of harmonic current generated by the converter and can be adjusted by the harmonic sharing factor K_h.

Unbalanced loading may be present and the unbalanced current should be shared between the converters in such a way that voltage asymmetry at the load busses is reduced. A method is developed [21] which is based on setting the negative sequence voltage to compensate a part of the negative sequence current produced by positive sequence voltage that occurs during unbalanced loading. The amount of this part depends on the share of converter for unbalanced current generation. As mentioned above, unbalanced current of an asymmetrically supplied load in terms of CPC power theory has two counter-rotating parts. One is with respect to positive sequence voltage and the other with respect to negative sequence voltage. Here, the calculation is formed to share the negative sequence part of the unbalance current as

(29) $$\boldsymbol{U}_1^N = \frac{\boldsymbol{A}_1^P}{\boldsymbol{Y}_{d1}} \boldsymbol{U}_1^P$$

Simulations for a system in the configuration of Fig. 4 were performed to validate the reference generator shown in Fig. 6. It was assumed that due to different ratings of the power converters sharing of various components of the load current should be in different proportions. Due to smaller capacity of the energy supply as well as a smaller converter rating, VSC 1 is able to generate half as much active and reactive power as VSC 2. Unbalanced current also is considered to be shared between the two converters with proportion to half for VSC 1 with respect to VSC 2. Since harmonic currents should be much less than fundamental current components VSC 1 is tasked to generate twice as much harmonic current as VSC 2. Figures 7, 8, 9, and 10 show active, reactive, harmonic and unbalance current sharing between the two sources, both with and without the unbalanced and harmonic generating loads. There is a constant balanced load in the grid and an unbalanced and a harmonic generating load are switched on at t=1s and switched off at t=2s. It can be seen that current components are shared between the two sources with the predefined sharing factors.

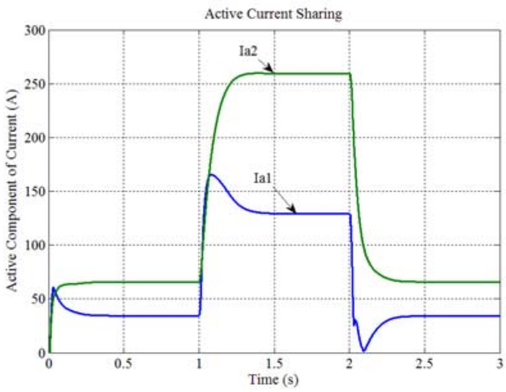

Figure 7. Active current sharing between two converters.

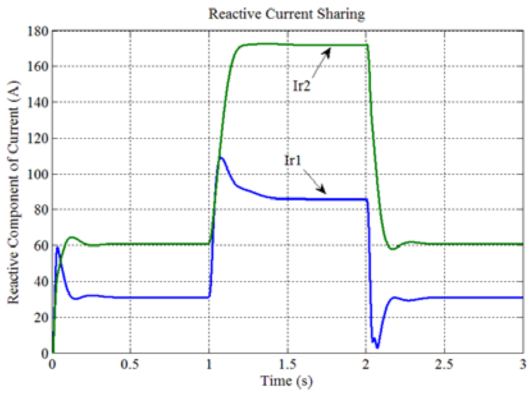

Figure 8. Reactive current sharing between two converters.

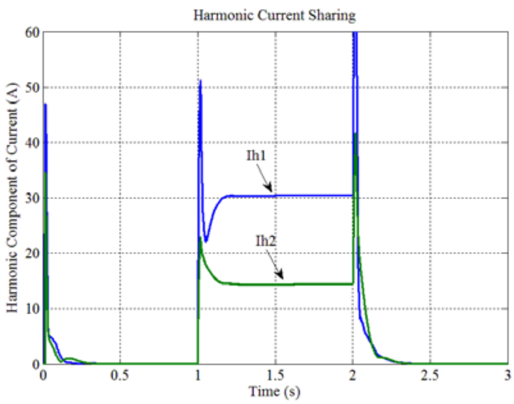

Figure 9. Harmonic current sharing between two converters.

Conclusions

The applicability of a particular reference generation technique to switching compensator control depends on the goals of compensation as well as expected system conditions. For the case of non-sinusoidal and asymmetrical supply conditions the extraction of positive sequence voltage fundamental is needed.

Coordinated control of the demanded current among converters in an autonomous microgrid provides a mechanism for optimization of the microgrid operation. Capabilities of interface power converters in providing each component of current may vary due to the availability of primary sources such as photo or wind, converter rating, converter structure and switching frequency of the converter. A reference signal generation method that allows independent control of load current components to be shared among sources in a microgrid was presented.

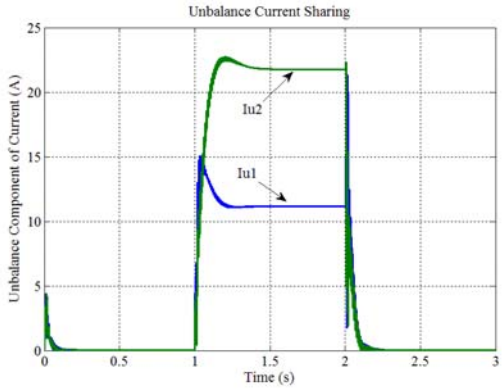

Figure 10. Unbalance current sharing between two converters.

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