2

Principles of Electrical Power Control

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2.1 Power Theory

The term power theory of circuits can be understood as the state of knowledge on their power properties. In that sense it is a set of true statements, interpretations, definitions and equations describing these properties [1]. The theory of power, understood that way, is a collective product of those who seek an answer to the question why a load with the active power P usually demands a power source with an apparent power S greater than its active power [2]. This question is closely related to the need for interpretation of power phenomena in electric circuits. Another factor is of a practical nature – power theory attempts to answer the question how the apparent power of the source can be reduced without the reduction in the load active power.

2.1.1 Critical Review of Classical Power Theory

In the 1920s two major trends in power theory had developed. The first uses Fourier series expansion to describe power properties of a circuit. Since electric quantities are regarded as sums of components with different frequencies, the electric circuit properties are defined in the frequency domain. Budeanu's power theory [3] is the most widespread theory in the frequency domain. Almost simultaneously, another trend has emerged which does not employ Fourier series and emphasizes defining the circuit power properties in the time domain. Since its conception the power theory in time domain is associated with Fryze's name [4]. The existence of these two trends has been evident in power theory development in the past as well as the present.

2.1.1.1 Single-phase Circuits Under Sinusoidal Conditions

This case, the simplest in terms of interpretation, is a starting point for all further considerations. If a linear load is supplied with a sinusoidal voltage (see Figure 2.1)

$$v = \sqrt{2} V_{RMS} \sin(\omega_{(1)} t - \varphi_u) \tag{2.1}$$

and the source current value is

$$i = \sqrt{2} I_{RMS} \sin(\omega_{(1)} t - \varphi_i) \tag{2.2}$$

where V_{RMS} and I_{RMS} are the RMS values of supply voltage v and load current I; $\varphi = \varphi_u - \varphi_i$ – phase angle between voltage v and current i.

The source's instantaneous power p, which is a measure of energy flow rate w from the source to the receiver, is (for $\varphi_u = 0$, $\varphi = \varphi_i$)

$$p = v \cdot i = 2 V_{RMS} I_{RMS} \sin \omega_{(1)} t \sin(\omega_{(1)} t - \varphi) = p_a + p_b \tag{2.3}$$

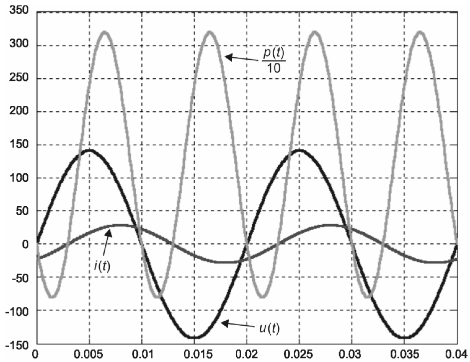


Figure 2.1. The waveforms of supply voltage u, load current i and instantaneous power p for an AC circuit with a linear (resistance-inductive) load under a steady-state operation (φ_u=0) [5]

Thus the instantaneous power p can be decomposed into the nonnegative component p_a and the oscillatory component p_b. The waveforms of separated components of instantaneous power p are shown in Figure 2.2.

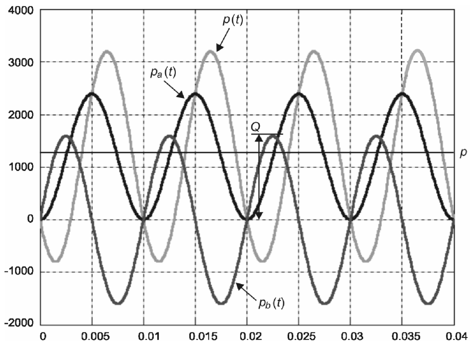


Figure 2.2. The waveforms of separated components of instantaneous power p [5]

The reactive power $Q = V_{RMS} I_{RMS} \sin\varphi$, in a circuit under sinusoidal conditions, is interpreted as the amplitude of the p_b component of the instantaneous power. According to the definition, the active power P equals the average value (DC component) over one period T of the instantaneous power p

$$P = \frac{1}{T}\int_0^T p(t)dt = V_{RMS} I_{RMS} \cos\varphi = S\cos\varphi \tag{2.4}$$

where S is the apparent power.

The source current can be expressed in the form

$$i = \sqrt{2} I_{RMS} \cos\varphi \sin\omega_{(1)} t + \sqrt{2} I_{RMS} \sin\varphi \cos\omega_{(1)} t = \sqrt{2}\frac{P}{V_{RMS}} \sin\omega_{(1)} t + \\ + \sqrt{2}\frac{Q}{V_{RMS}} \cos\omega_{(1)} t \tag{2.5}$$

and, thus, considering the orthogonality of both components, the current RMS value is

$$I_{RMS} = \sqrt{\left(\frac{P}{V_{RMS}}\right)^2 + \left(\frac{Q}{V_{RMS}}\right)^2} \tag{2.6}$$

and the equation which determines the apparent power value $S^2 = P^2 + Q^2$ is satisfied. The magnitude of the complex power

$$\underline{S} = \underline{V}\underline{I}^* = Ve^{j\varphi_u}(Ie^{j\varphi_i})^* = Se^{j(\varphi_u - \varphi_i)} = Se^{j\varphi} = S\cos\varphi + jS\sin\varphi = P + jQ \tag{2.7}$$

is equal to the apparent power S. The parameter $cos\varphi$, termed the displacement power factor, is defined as $DPF = \cos\varphi = P/S$. Reactive power compensation to the value of Q=0 reduces the source current to minimum.

2.1.1.2 Three-phase Circuits Under Sinusoidal Conditions

A three-phase, three-wire electric circuit, as shown in Figure 2.3, is considered.

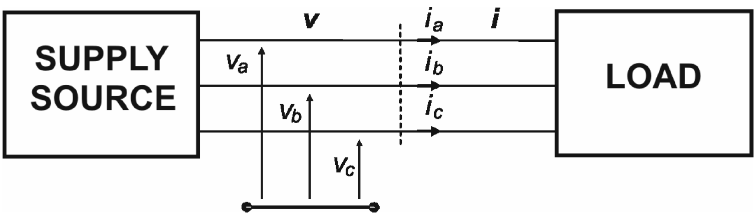


Figure 2.3. Phase voltages and currents at the cross-section *a-b-c*

Phase voltages and currents are expressed in the form of column vectors: $v = v = [v_a, v_b, v_c]^T$ and $i = i = [i_a, i_b, i_c]^T$. Figure 2.4 shows the sinusoidal symmetrical waveforms of supply voltage v and load current i in the three-phase electric circuit with linear load. This is the simplest case from the point of view of power phenomena that take place in three-phase electrical circuits.

Instantaneous power p_{3f} of a three-phase circuit takes the form of

$$p_{3f} = p_a + p_b + p_c = v_a \cdot i_a + v_b \cdot i_b + v_c \cdot i_c \tag{2.8}$$

In this case the waveform of instantaneous power p_{3f} is constant, in contrast to the single-phase circuit (Figures 2.1 and 2.2). The relations of powers of three-phase circuit take the form of

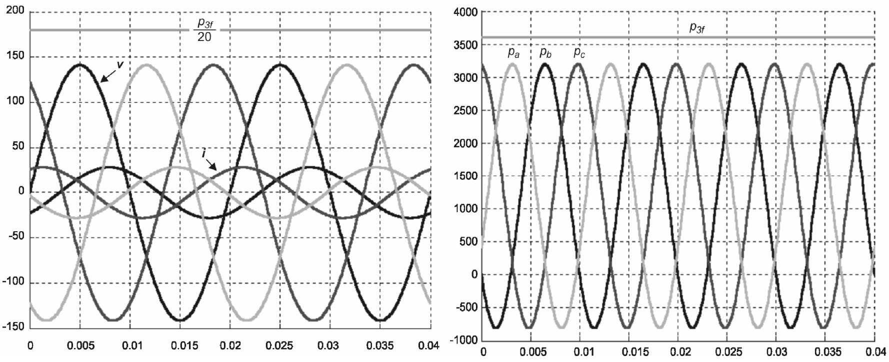
$$P_a = V_{RMS,a} I_{RMS,a} \cos\varphi = P_b = P_c = P \Rightarrow P_{3f} = 3P \tag{2.9}$$

$$Q_a = V_{RMS,a} I_{RMS,a} \sin\varphi = Q_b = Q_c = Q \Rightarrow Q_{3f} = 3Q \tag{2.10}$$

$$S_a = S_{a(1)} = V_{RMS,a} I_{RMS,a} = S_b = S_c = S \Rightarrow S_{3f} = S_{3f(1)} = 3S \tag{2.11}$$

and power factors PF_{3f} and DPF_{3f} take the form of

$$PF_{3f} = DPF_{3f} = P_{3f} / S_{3f} \tag{2.12}$$



a b

Figure 2.4. The waveforms of: **a** supply voltage v, load current i; **b** phase instantaneous powers p_a, p_b, p_c and instantaneous power p_{3f} (balanced resistive load) [5]

In the latter case the interpretation, definitions and equations describing these properties for single-phase circuits with sinusoidal supply voltage and current were applied.

In three-phase systems it is impossible, on the basis of the instantaneous power, to separate the reactive power. Reactive power interpretation according to what exists in one-phase circuits cannot be applied, so it loses its general physical sense.

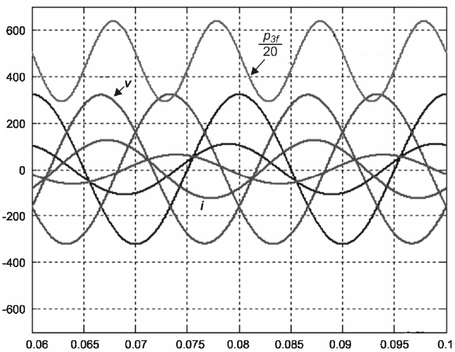


Figure 2.5. The waveforms of supply voltage v, load current i and instantaneous power p_{3f} in the three-phase thee-wire electric circuit with and unbalanced resistive load [5]

In three-phase circuits, however, a phenomenon occurs that was not present in single-phase circuits, namely the asymmetry of supply voltages v and/or load currents i waveforms. It is assumed that the asymmetry of resistive load currents is the only cause for the phase shift between the voltages and currents in three-phase three-wire electric circuits (despite the lack of passive elements). Therefore, the displacement power factor DPF_{3f} value is less than 1, $DPF_{3f} < 1$.

Figure 2.5 shows the waveforms of voltages v and currents i in three-phase three-wire electric circuits with unbalanced resistive load. One can see that the instantaneous power p_{3f} is no longer constant. In this situation the interpretation, definitions and formulas for single-phase circuits do not hold. Any consideration of a three-phase circuit as composed of three single-phase circuits could lead to a major misinterpretation of power phenomena in such a circuit. It has to be considered a single three-phase circuit.

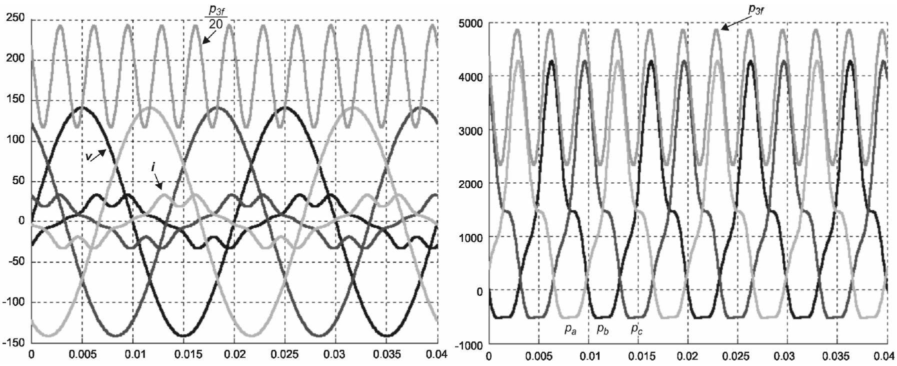


Figure 2.6. The waveforms of: **a** supply voltage *v*, load current *i*; **b** phase instantaneous powers p_a, p_b, p_c and instantaneous power p_{3f}

Figure 2.6 shows sinusoidal symmetrical waveforms of the supply voltages *v* and load current *i* in the three-phase electric circuit with symmetrical non-linear load. The presence of distorted phase load currents results in the fact that instantaneous power p_{3f} is no longer constant. However, in this case it is possible to use the interpretation, definitions and formulas for single-phase circuits. It is not possible if the waveforms of supply voltages *v* and/or load currents *i* are asymmetrical.

The extension of the apparent power concept to multi-phase systems has lead to many controversies. Essentially, three definitions are in use:

- Arithmetic apparent power $S_A = V_{RMS,a} I_{RMS,a} + V_{RMS,b} I_{RMS,b} + V_{RMS,c} I_{RMS,c}$;
- Geometric apparent power [6] $S_G = \sqrt{P_{3f}^2 + Q_{3f}^2}$;
- Buchholz's apparent power [3] $S_B = \sqrt{V_a^2 + V_b^2 + V_c^2} \cdot \sqrt{I_a^2 + I_b^2 + I_c^2}$.

As long as the supply voltage is sinusoidal and symmetrical, and the load is balanced, these relations give the same correct result. If one of the above-mentioned conditions is not met the obtained results will differ. The consequence of this will be that we get different values of power factors for the same electric circuit. For obvious reasons such a situation is neither desired nor admissible. In publications [7] it has been proved that in such a case only the Buchholz's definition of apparent power S_B allows for the correct calculation of apparent power, and therefore of the power factor value. Moreover, it can be proven that the Buchholz's apparent power can be extended to circuits with non-sinusoidal voltages and currents.

2.1.1.3 Powers in Circuits with Non-sinusoidal Voltages and Currents

The choice of the presented power theories is subjective; only those theories which in the author's opinion are most widely used will be discussed.

The works of Steinmetz [2] should certainly be mentioned here – he was the first who, examining the example of a mercury rectifier, found that the apparent power is greater than the active power due to the distortion of a current with respect to a sinusoidal voltage. This finding worked the inception of power theories of electric circuits with non-sinusoidal voltages

$$v = \sum_{n=0}^{\infty} v_{(n)} \tag{2.13}$$

and currents

$$i = \sum_{n=0}^{\infty} i_{(n)} \tag{2.14}$$

where n is the harmonic order.

Budeanu Theory (Frequency Domain)[8]

The active and reactive powers are defined as superposition of active and reactive powers of all harmonics, respectively

$$P = \frac{1}{T}\int_0^T v \cdot i dt = V_0 I_0 + \sum_{n=1}^{\infty} V_{RMS(n)} I_{RMS(n)} \cos\varphi_{(n)} = \sum_{n=0}^{\infty} P_{(n)} \tag{2.15}$$

$$Q_B = \sum_{n=1}^{\infty} V_{RMS(n)} I_{RMS(n)} \sin\varphi_{(n)} = \sum_{n=1}^{\infty} Q_{(n)} \tag{2.16}$$

(satisfying the principle of energy balance) and the distortion power

$$D = \sqrt{S^2 - (P^2 + Q_B^2)} \tag{2.17}$$

where $I_{RMS(n)}$, $V_{RMS(n)}$ are RMS values of n-th harmonic of current and voltage; $\varphi_{(n)}$ – phase angle between voltage v and current i n-th harmonics; V_0, I_0 are the DC components.

According to this theory the apparent power is determined as

$$S = V_{RMS} I_{RMS} = \sqrt{\sum_{n=0}^{\infty} V_{RMS(n)}^2 \sum_{n=0}^{\infty} I_{RMS(n)}^2} = \sqrt{P^2 + Q_B^2 + D^2} \tag{2.18}$$

Errors in this theory have been demonstrated for the first time in the work [9] proving that:

- It suggests a misinterpretation of power phenomena in circuits with periodic distorted voltages and currents. The defining formula introduces the distortion power D as a completion of existing powers to the apparent power $S=V_{RMS}I_{RMS}$ (Schwartz's inequality), and does not link it directly with the load properties. The distortion power is not related to the current distortion against the voltage and has absolutely no physical meaning. A necessary condition for the distortion power zero value is the load admittance having the same value $Y_{(n)}$ for each voltage harmonic, *i.e.*, $Y_{(n)} = Y_{(n)}\exp(j\varphi_{(n)}) = const$. At the same time the necessary condition for the lack of current waveform distortion against the voltage is that the load admittance for each harmonic takes the value $Y_{(n)} = Y\exp(-jn\omega_{(1)}t) = Y\exp(-jn\varphi)$. These conditions are mutually exclusive. If, under non-sinusoidal supply voltage, the distortion power $D=0$, the load current must be distorted against the voltage. When, under the same conditions, the load current is not distorted against the voltage, the distortion power D cannot be zero. The properties of distortion power are therefore quite the opposite to what its name suggests;
- The reactive power according to Budeanu's definition is not a measure of energy oscillation. This quantity can be equal to zero though one-directional power components may have significant amplitudes and cause power oscillation;
- Moreover, powers Q_B and D are of no significance for the power factor correction. The reactive power cannot be minimized employing this theory and therefore the power factor cannot be improved. This theory does not allow one to determine the compensation capacitance at which the power factor attains its highest value. Full compensation of reactive power Q_B in some situations may even worsen the power factor;
- There is no direct relationship between the RMS current value and distortion power. The RMS value of a source current harmonic is

$$I_{RMS(n)} = \sqrt{\left(\frac{P_{(n)}}{V_{RMS(n)}}\right)^2 + \left(\frac{Q_{(n)}}{V_{RMS(n)}}\right)^2}$$

Since the current harmonics, as the waveforms with different frequencies, are mutually orthogonal, the RMS source current value can be expressed in the form

$$I_{RMS} = \sqrt{\sum_{n=0}^{N} I^2_{RMS(n)}} = \sqrt{\sum_{n=0}^{N}\left(\left(\frac{P_{(n)}}{V_{RMS(n)}}\right)^2 + \sum_{n=1}^{N}\left(\frac{Q_{(n)}}{V_{RMS(n)}}\right)^2\right)}$$

It is therefore evident that the RMS source current value does not depend on the sum of reactive powers of individual harmonics $Q_{(n)}$, *i.e.*, the reactive power according to Budeanu, but on the sum of their squares. For unchanged values of $P_{(n)}$ the RMS source current value is minimum if the reactive power of each harmonic $Q_{(n)}$ equals zero, and not when Budeanu reactive power is zero. Thus the zero value of Budeanu reactive power is not the necessary condition for the minimum RMS current value – it is only a sufficient condition.

A special case of considerations regarding this theory is the analysis of a circuit with the sinusoidal supply voltage and non-linear load. Therefore, the equation on the load current is as follows (see Figure 2.7)

$$i = \sum_{n=1}^{\infty} \sqrt{2} I_{RMS(n)} \sin(n\omega_{(1)} t - \varphi_{(n)}) \tag{2.19}$$

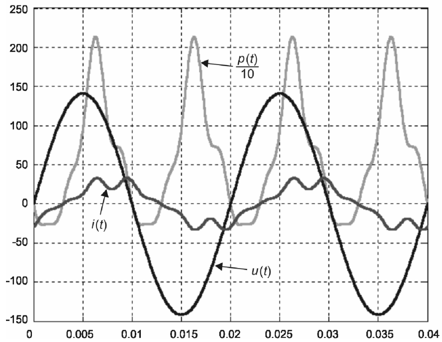


Figure 2.7. The waveforms of voltage *v*, current *i* and instantaneous power *p* for an AC circuit with a non-linear load under a steady-state operation [5]

In that case the equation of instantaneous power *p* is

$$\begin{aligned} p &= V_{RMS} I_{RMS(1)} \cos\varphi_{(1)} (1 - \cos 2\omega_{(1)} t) - \\ &- V_{RMS} I_{RMS(1)} \sin\varphi_{(1)} \sin 2\omega_{(1)} t + \\ &+ \sum_{n=2}^{\infty} 2 V_{RMS} I_{RMS(n)} \sin\omega_{(1)} t \sin(n\omega_{(1)} t - \varphi_{(n)}) \end{aligned} \tag{2.20}$$

The definitions of active power $P_{(1)} = V_{RMS} I_{RMS(1)} \cos\varphi_{(1)} = P$ and reactive power $Q_{(1)} = V_{RMS} I_{RMS(1)} \sin\varphi_{(1)} = Q$ were specified for the first harmonic. The equation of apparent power *S* changes, as follows

$$S = V_{RMS} I_{RMS} = V_{RMS} \sqrt{I^2_{RMS(1)} + \sum_{n=2}^{\infty} I^2_{RMS(n)}} = \sqrt{P^2_{(1)} + Q^2_{(1)} + D^2} \tag{2.21}$$

In this way the apparent power in the first harmonic domain $S_{(1)}$ and the distortion power *D* were separated.

Therefore, in this case of non-linear load the power factor denoted as *PF* was defined as

$$PF = \frac{P_{(1)}}{S} = \frac{P_{(1)}}{\sqrt{S_{(1)}^2 + D^2}} = \frac{1}{\sqrt{1 + THD_I^2}} \cos\varphi_{(1)} = \frac{1}{\sqrt{1 + THD_I^2}} DPF \qquad (2.22)$$

where THD_I is the so called - total harmonic distortion of the current *i* (the same form for the voltage).

Fryze Theory (Time Domain)[4]
Fryze introduced a number of important and lasting elements to the theory of power. The most important of them are decomposition of a source current into orthogonal components related to the electric energy phenomena, identification of the active current as a separate quantity, and defining power quantities without employing Fourier series, *i.e.*, in the time domain. Fryze decomposed the source current into the active component

$$i_P = \frac{P}{V_{RMS}^2} \cdot v = G \cdot v \qquad (2.23)$$

and the reactive component

$$i_{QF} = i - i_P \qquad (2.24)$$

The active current is the current of a resistive load with conductance *G* (termed equivalent conductance) having the same active power *P* at the same voltage *v*. The portion of the source current remaining after subtracting the active current is the Fryze's reactive current i_{QF}. The scalar product of such defined currents is zero, *i.e.*, $(i_P, i_{QF}) = 0$, so they are mutually orthogonal and their RMS values satisfy the equitation

$$I_{RMS}^2 = I_P^2 + I_{QF}^2 \qquad (2.25)$$

Multiplying both sides of this equation by the square of the RMS voltage value V_{RMS}, we obtain the equation of power $S^2 = P^2 + Q_F^2$ with the reactive power defined by the formula $Q_F = V_{RMS} I_{QF}$. This power does not satisfy the principle of energy conservation and is always positive, which precludes determining whether the power factor is leading or lagging.

The Fryze power theory does not explain the physical sense of the reactive current i_{QF}, except by concluding that it is a needless load for the source and causes extra transmission losses. The Fryze theory, moreover, does not explain either what phenomena in a circuit give rise to this current or the load parameter's influence on its RMS value.

This theory does not allow determination parameters of LC passive compensators, whereas a current source connected in parallel with the load and generating the current $(-i_{QF})$ corrects power factor to unity. Such a source, with its control circuits, is an active power filter. Its principle of operation is an immediate conclusion inferred from the Fryze's power theory.

Orthogonal decompositions are valid for circuits supplied from an ideal source, but for circuits supplied from sources with nonzero internal impedance they do not hold. There are, however, proposals for solution of the optimisation task that minimizes given quality index, *e.g.*, the RMS value of the source current. Such a solution allows one to obtain, under given constraints, the energy-optimal state of an electric system, by using compensators with parameters determined using this method [10, 11].

In their original form, Budeanu's and Fryze's theories describe power properties exclusive of single-phase circuits. They can, however, be easily extended to balanced three-phase circuits.

Shepherd and Zakikhani Power Theory (Frequency Domain)[12]
For a load with the current

$$i = \sqrt{2}\sum_{n=1}^{\infty} I_{RMS(n)} \cos(n\omega_{(1)}t - \beta_{(n)}) \tag{2.26}$$

supplied with the voltage

$$v = \sqrt{2}\sum_{n=1}^{\infty} V_{RMS(n)} \cos(n\omega_{(1)}t - \alpha_{(n)}) \tag{2.27}$$

the resistive current

$$i_R = \sqrt{2}\sum_{n=1}^{\infty} I_{RMS(n)} \cos\varphi_{(n)} \cos(n\omega_{(1)}t - \alpha_{(n)}) \tag{2.28}$$

and reactive current have been defined as

$$i_r = \sqrt{2}\sum_{n=1}^{\infty} I_{RMS(n)} \sin\varphi_{(n)} \sin(n\omega_{(1)}t - \alpha_{(n)}) \tag{2.29}$$

where $\varphi_{(n)} = \alpha_{(n)} - \beta_{(n)}$.

The scalar product of these currents is zero, so they are mutually orthogonal and their RMS values satisfy the relation

$$I_{RMS}^2 = I_{RMS,R}^2 + I_{RMS,r}^2 \tag{2.30}$$

Multiplying both sides of this equation by the square of RMS voltage value we obtain an equation of the source power

$$S = V_{RMS} I_{RMS} = \sqrt{V_{RMS}^2 I_{RMS,R}^2 + V_{RMS}^2 I_{RMS,r}^2} = \sqrt{S_R^2 + Q_{SZ}^2} \tag{2.31}$$

Powers S_R and Q_{SZ} do not satisfy the principle of power balance. The current i_r can be compensated for a finite number of harmonics by means of a two terminal LC network connected in parallel with the load [13].

The Shepherd's and Zakihani's power theory for the first time allowed are to obtain a result of practical significance since it enables one to calculate such compensating capacitance that ensures a maximum power factor value of the supply source (assuming the supply source is an ideal voltage source. *i.e.*, RMS values of the voltage harmonics at the load are independent of the compensating capacitance, which is not satisfied in real power supply systems). This capacitance is termed the optimal capacitance (in the sense of minimization of the source current RMS value)

$$C_{opt} = \frac{\sum_{n=1}^{N} n V_{(n)} I_{(n)} \sin \varphi_{(n)}}{\omega_{(1)} \sum_{n=1}^{N} n^2 V_{(n)}^2} \tag{2.32}$$

The decomposition of power lacks a single, well defined power quantity, namely active power. Sharon attempted to eliminate this inconvenience separating from the power S_R a quantity which he termed associated reactive power

$$S_C = \sqrt{S_R^2 - P^2} \tag{2.33}$$

Thus, the equation of power according to Sharon [14] takes the form

$$S = \sqrt{P^2 + Q_{SZ}^2 + S_C^2} \tag{2.34}$$

This equation, however, does not explain the nature of power phenomena in a circuit and their relationship with the load properties. The Shepherd and Zakichani theory has never been extended to polyphase circuits.

Kusters and Moore Theory of Power (Time Domain)[15]

The theory is based on the source current decomposition, for a resistive-inductive load, into an active current, capacitive reactive current i_{qC} and the residual reactive current i_{qCr}. These currents are defined by the formulas

$$i_{qC} = \frac{\frac{1}{T}\int_0^T \frac{dv}{dt} i dt}{\left(\frac{dv}{dt}\right)^2_{RMS}} \frac{dv}{dt} = \frac{\left(\frac{dv}{dt}, i\right)}{\left(\frac{dv}{dt}\right)^2_{RMS}} \frac{dv}{dt} \tag{2.35}$$

and

$$i_{qCr} = i - i_P - i_{qC} \tag{2.36}$$

The equation of power according to Kusters and Moore has the form

$$S = \sqrt{P^2 + Q_C^2 + Q_{Cr}^2} \tag{2.37}$$

where $Q_C = V_{RMS} I_{RMS,qC} \operatorname{sgn}(dv/dt, i)$ ("*sgn*" denotes the sign of a scalar product); $Q_{Cr} = V_{RMS} I_{RMS,qCr}$.

According to the authors of this theory, the capacitive reactive power Q_C can be fully compensated by means of a capacitor with capacitance

$$C_{opt} = -Q_C / \left[V_{RMS} \left(\frac{dv}{dt}\right)^2_{RMS} \right] \tag{2.38}$$

connected in parallel to the load. The source power factor attains its highest value for that capacitance. It is the same optimal capacitance as determined from the Shepherd and Zakikhani theory. Calculating the optimal capacitance from this formula requires the knowledge of the RMS values of current and voltage harmonics and their phase shifts. Kusters and Moore theory allows one to calculate this capacitance directly in the time domain. On the basis of this theory, Page [16] proposed a method for computing the parameters of a shunt LC compensator.

Czarnecki Power Theory (Frequency Domain)[17]

Czarnecki, taking the concept of active current i_p from Fryze's theory, the concept of reactive current i_r from the Shepherd and Zakikhani theory and introducing the new component i_s termed scattered current, proposed orthogonal decomposition of the current of a source feeding a lineal load in the form $i = i_p + i_r + i_s$. In this case the reactive current according to Fryze is expressed as the sum of currents i_r and i_s, whereas the resistive current according to Shepherd and Zakikhani is the sum of currents i_p and i_s. If N is the set of supply voltage harmonic orders n

$$v = \sqrt{2}\,\mathrm{Re} \sum_{n \in N} V_{RMS(n)} \exp(jn\omega_{(1)} t) \tag{2.39}$$

and then the current components i_s and i_r are defined by formulas

$$i_S = \sqrt{2}\,\mathrm{Re}\sum_{n\in N}\left(G_{(n)} - G_e\right)V_{RMS(n)}\exp(jn\omega_{(1)}t) \tag{2.40}$$

$$i_r = \sqrt{2}\,\mathrm{Re}\sum_{n\in N} jB_{(n)}V_{RMS(n)}\exp(jn\omega_{(1)}t) \tag{2.41}$$

where $G_{(n)} + jB_{(n)}$ is the load admittance for the n-th harmonic and $G_e\,(=G)$ is the equivalent conductance defined according to Fryze's theory.

Currents i_p, i_s and i_r are mutually orthogonal, thus

$$I_{RMS} = \sqrt{I^2_{RMS,P} + I^2_{RMS,S} + I^2_{RMS,r}} \tag{2.42}$$

According to this equation the RMS value of the source current I_{RMS} in a linear circuit with non-sinusoidal voltage is greater than the active current RMS value $I_{RMS,P}$, not only when the load susceptance for voltage harmonics $B_{(n)}$ is nonzero, but also when the load conductance $G_{(n)}$ varies with frequency.

Decomposition of the source current in a linear circuit into the active, scattered and reactive currents was extended to non-linear circuits by means of separation of the generated current i_g, which consists of harmonics generated in a load due to its non-linearity or the circuit time-variant parameters. Thus, in the general case, the current was finally decomposed into four orthogonal components: $i = i_p + i_r + i_s + i_g$. The proposed components of current, even if they are only mathematical quantities (only the current is a physical quantity), exhibit properties which distinguish them from (infinitely many) other components. They can be associated with various physical phenomena (hence the theory is referred to as the theory of the current's physical components) and, consequently, with various components of reactive power.

2.1.1.4 Three-phase Circuits

A number of power theories in three-phase circuits with periodic non-sinusoidal voltages and currents have been proposed. This issue still provokes discussion and controversy. The most popular power theory, commonly employed in active filters control, has been proposed by Akagi and co-authors; it is known as the *p-q* power theory.

One of the most interesting power theories (known as the power theory based on the current's physical components) was presented by Czarnecki. This theory is a proposal of the physical interpretation of power phenomena occurring in electric circuits under unbalanced conditions and in the presence of non-sinusoidal waveforms. The complete Czarnecki theory for three-phase unbalanced circuits with periodic non-sinusoidal source voltage was presented in his work in 1994 [18].

Both theories are of particular importance for the development of power theory.

2.1.2 Instantaneous Power Theory

Nabae and Akagi instantaneous reactive power *p-q* theory [19–23] not only provides theoretical basis for control algorithms for switching compensators but also became the method of describing power properties of three-phase circuits. It is popular although it can exclusively be employed to analyze three-phase circuits and therefore is not a general power theory. The description of power properties of electric circuits, using instantaneous voltage and current values, without the use of Fourier series *i.e.*, in time domain, to a great extent explains the interest in this concept. Since a compensator control algorithm based on the *p-q* theory involves no harmonic analysis, the number of necessary mathematical operations is reduced with respect to frequency-based methods.

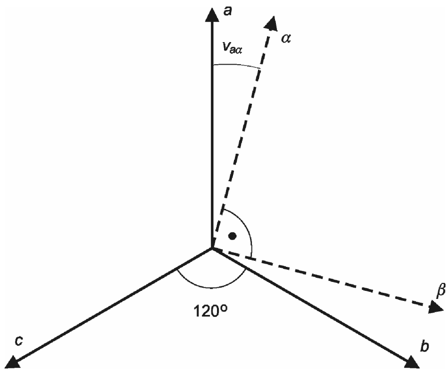


Figure 2.8. Transformation of *a-b-c* coordinates into *α-β-0* coordinates

The instantaneous reactive power theory employs the Clark transformation of three-phase voltages and currents in natural phase coordinates (Figure 2.8), into orthogonal *α-β-0* coordinates. The transformation is performed computing the instantaneous values according to Equation 2.43, where υ_{ax} is the phase shift angle between the x axis of the natural three-phase coordinate system and the α axis of the orthogonal coordinate system; see Figure 2.8.

$$\begin{bmatrix} F_\alpha \\ F_\beta \\ F_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\upsilon_{a\alpha} & \cos\upsilon_{ab} & \cos\upsilon_{ac} \\ -\sin\upsilon_{a\alpha} & -\sin\upsilon_{ab} & -\sin\upsilon_{ac} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} F_a \\ F_b \\ F_c \end{bmatrix} \tag{2.43}$$

Due to the fact that energy is mostly transferred by means of three-wire systems, the zero-sequence component in the transformation matrix can be omitted and considerations are confined to three-wire circuits supplied from balanced sources of three-phase sinusoidal voltages, where $i_a + i_b + i_c = 0$ and $v_a + v_b + v_c = 0$. Assuming additionally that axes a and α coincide, *i.e.*, $\upsilon_{a\alpha} = 0$, the Clark transformation of phase voltages and currents simplifies to

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{2.44}$$

and

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2.45}$$

The currents and voltages transformed orthogonal coordinates α-β are used to define the instantaneous real power

$$p = e_\alpha i_\alpha + e_\beta i_\beta = v_a i_a + v_b i_b + v_c i_c = \frac{dW}{dt} \tag{2.46}$$

and the instantaneous imaginary power

$$q = e_\alpha i_\beta - e_\beta i_\alpha = \frac{1}{\sqrt{3}}\left[i_a\left(v_c - v_b\right) + i_b\left(v_a - v_c\right) + i_c\left(v_b - v_a\right)\right] \tag{2.47}$$

Powers p and q are determined with a delay that results only from current and voltage sampling and the necessary computing time, *i.e.*, almost instantaneously.

The instantaneous real power p is the well-known instantaneous power of a load being the measure of the energy flow rate to the load, whereas there is no physical interpretation of the instantaneous imaginary power q.

Denoting instantaneous powers in axes α and β as p_α and p_β the instantaneous power p can be expressed as

$$\begin{aligned} p &= p_\alpha + p_\beta = e_\alpha i_{\alpha p} + e_\alpha i_{\alpha q} + e_\beta i_{\beta p} + e_\beta i_{\beta q} = \\ &= e_\alpha \frac{e_\alpha}{e_\alpha^2 + e_\beta^2} p - e_\alpha \frac{e_\beta}{e_\alpha^2 + e_\beta^2} q + e_\beta \frac{e_\beta}{e_\alpha^2 + e_\beta^2} p + e_\beta \frac{e_\alpha}{e_\alpha^2 + e_\beta^2} q = \\ &= p_{\alpha p} + p_{\alpha q} + p_{\beta p} + p_{\beta q} \end{aligned} \tag{2.48}$$

where $i_{\alpha p}$ – instantaneous active current in α axis; $i_{\beta p}$ – instantaneous active current in β axis; $i_{\alpha q}$ – instantaneous reactive current in α axis; $i_{\beta q}$ – instantaneous reactive current in β axis; $p_{\alpha p}$ – instantaneous active power in α axis; $p_{\alpha q}$ – instantaneous reactive power in α axis; $p_{\beta p}$ – instantaneous active power in β axis; $p_{\beta q}$ – instantaneous reactive power in β axis.

These components have no physical interpretations and do not participate in the energy transfer from the source to load.

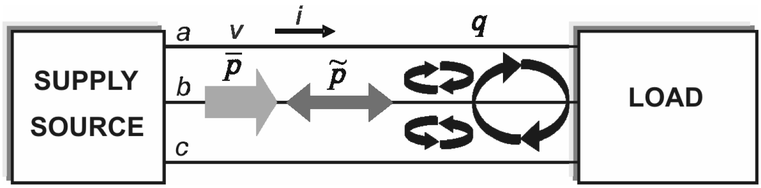


Figure 2.9. The *p-q* power theory – the graphical representation of defined power components in a three-phase circuit

The sum of the two remaining components (instantaneous active powers)

$$p_{\alpha p} + p_{\beta p} = p \tag{2.49}$$

is consistent with the common interpretation of an instantaneous power applied to three-phase circuits. Figure 2.9 shows the graphical representation of defined power components in a three-phase circuit.

When the load is non-linear and unbalanced the real and imaginary powers can be split into average and oscillating components, as follows

$$p = \bar{p} + \tilde{p} = \bar{p} + \tilde{p}_h + \tilde{p}_{2f_{(1)}} \tag{2.50}$$

and

$$q = \bar{q} + \tilde{q} = \bar{q} + \tilde{q}_h + \tilde{q}_{2f_{(1)}} \tag{2.51}$$

where $\bar{p}, \bar{q}$ – average components; $\tilde{p}_h, \tilde{q}_h$ – oscillating components (*h* – "*harmonic*"); $\tilde{p}_{2f_{(1)}}, \tilde{q}_{2f_{(1)}}$ – oscillating components ($2f_{(1)}$ – with double frequency of the fundamental component frequency).

According to the *p-q* power theory, the current of three-phase unbalanced non-linear load has been decomposed into four components

$$i = i_{\bar{p}} + i_{\bar{q}} + i_h + i_{2f_{(1)}} \tag{2.52}$$

where $i_{\bar{p}}$ – is associated with $\bar{p}$; $i_{\bar{q}}$ is associated with $\bar{q}$; i_h is associated with $\tilde{p}_h$ and $\tilde{q}_h$, *i.e.*, with the presence of harmonics in voltage and current waveforms; $i_{2f_{(1)}}$ is associated with $\tilde{p}_{2f_{(1)}}$ and $\tilde{q}_{2f_{(1)}}$, *i.e.*, the unbalance load currents.

From these power components the current components in the α-β coordinates can be calculated

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \cdot \begin{bmatrix} p \\ q \end{bmatrix} = \frac{1}{e_\alpha^2 + e_\beta^2} \begin{bmatrix} e_\alpha & -e_\beta \\ e_\beta & e_\alpha \end{bmatrix} \cdot \begin{bmatrix} p \\ q \end{bmatrix} \tag{2.53}$$

Then, using the Clark inverse transformation, the currents in the natural *a-b-c* coordinates can be calculated. Depending on which component of the source current has to be eliminated, appropriate power components should be substituted.

The instantaneous power theory, in its original form, should not be applied to circuits unbalanced or supplied with distorted voltage. When a linear load is supplied with distorted periodic voltage, the distortions caused by the supply voltage harmonics are still present in the source current after the compensation.

The author of [24] has demonstrated that the instantaneous power *p-q* theory suggests an erroneous interpretation of power properties of three-phase circuits. According to this theory, the instantaneous imaginary current may occur in the current of a load with zero reactive power whereas the instantaneous active current may occur in the current of a load with zero active power. Moreover, these currents are non-sinusoidal, even if the supply voltage is sinusoidal and the load contains no harmonic sources.

If linear, time-invariant three-phase loads in a three-wire system supplied with balanced sinusoidal voltage are considered, the following three features are decisive for their power properties under the circuit steady state conditions. These are:

- Irreversible conversion of electric energy into other forms of energy determined by the load active power P;
- Reversible accumulation of energy in the load reactive elements, determined by the load reactive power Q, causing the current phase shift with respect to the voltage;
- The load unbalance resulting in the asymmetry of supply currents, determined by the distortion power D of a load.

The instantaneous power *p-q* theory employs only two power components: p and q. Thus, the pair of powers, measured at any given instant of time, does not allow determining three powers P, Q and D, and therefore does not allow determining the power properties of a three-phase load. The knowledge of instantaneous powers p and q at any given instant of time does not allow the drawing of any conclusions regarding the load properties. For this purpose the instantaneous powers p and q must be monitored over the entire period of their variability. Power properties of three-phase three-wire loads with sinusoidal currents and voltages are specified in terms of the active, reactive and unbalanced power. The active power P equals the average value of instantaneous active power p: $P = \overline{p}$. The reactive power Q equals the negative value of average instantaneous imaginary power q: $Q = -\overline{q}$. Thus, the active and reactive powers of a load can only be known after computing these values. Still the unbalanced power D remains unknown, what is the main drawback of the discussed theory. This concept lacks any power component uniquely associated with the load unbalance.

Similarly, since the sum of the squares of powers *p* and *q* does not define the apparent power *S*, the power factor $\lambda = P/S$ cannot be instantaneously determined and therefore cannot be determined whether or not the load requires reactive power compensation.

The *p-q* power theory turned out to be a very useful tool for developing the control algorithms of active power filters.

2.2 General Problems and Solutions of Control in Smart Power Systems

2.2.1 Control in Smart Power Systems

A substantial growth in the use of DR has been experienced in power systems in many countries. This growth is influenced by several factors including pressure to reduce CO^2 emissions, re-regulation of electric power industry, progress in generation technologies, cost reduction in materials, economic incentives (*e.g.*, special purchase tariffs for electric energy produced by Renewable Energy Sources (RES) and Combined Heat and Power (CHP) systems or plants making use of waste). The exploitation of DR leads to the connection of DG to low voltage and medium voltage grids and has given rise to new and often challenging problems. The distribution networks were not initially designed to host generation and they were usually operated with energy flowing in only one direction, namely from the substation to the customers, which is no longer true with the advent of DR generating units. DR deployment has often led system operators, electric utilities, governments or regulatory boards to define technical specifications for the grid connection and operation of DG units. The issues that came into the spotlight with the advent of DR generating units on distribution networks include: steady-state and short-circuit current constraints; power quality; voltage profile, reactive power and voltage control; contribution to ancillary services; stability and capability of DR generating units to withstand disturbances; protection aspects and islanding and islanded operation.

Connection of large RES plants whose location is largely influenced by availability of primary energy source (*e.g.*, wind) poses problems of bulk transfer of large amounts of power from remote (previously not considered) locations to load centers. The existing transmission systems often lack the capacity for transferring such amounts of power due unavailability of transmission lines or limited capacities of existing transmission corridors. The transmission system therefore needs to be strengthened in order to ensure security of supply and to fulfil its role as a marketplace where electrical energy is freely bought and sold following the rules of fair competition. There are several options to increase the transfer capacity, ranging from the building of new transmission lines (which in many countries will be very difficult due to environmental and legislative constraints), increased deployment of smart transmission technologies, such as

HVDC lines and FACTS devices, to a better utilization of the existing network due to a more efficient operation and improved control and regulation.

The role of electrical power system, *i.e.*, to be able to meet the continually changing load demand for active and reactive power, to supply energy at minimum cost and with minimum ecological impact and to ensure that the quality of power supply meets minimum standards with regard to constancy of frequency, constancy of voltage and level of reliability, will remain basically the same in spite of the changed composition and characteristics of its constituting elements, be those primary sources of electrical energy (generators) or power electronics based control devices that facilitate required transfer and control of electrical power. They will be required to provide reliable, flexible and cost-effective power supply, fully exploiting the use of both large centralized generators and DR, ensuring at the same time that they are more than just massive integration of DR generating units into the grids. Adoption of more ambitious concepts related to active management of the distribution grids in particular is required, where responsive loads, storage devices and DG can be used together to improve the overall system efficiency, quality of electricity supply and operating conditions, leading to a fully active distribution network. Exploiting the active networks infrastructure (SmartGrids) requires intelligent tools that will help decision makers to assess the network impacts and benefits resulting from a wide deployment of DR (including RES) and optimize the operating performance of the system with a high penetration of RES and DR. The evolution of electrical power networks towards the fully active structure requires several intermediate steps including: definition of connection standards and operational rules (grid codes); identification of new protection schemes and new relay settings; definition of new control procedures and managing approaches, integrating DR generation, storage devices and responsive loads; feasibility evaluation regarding islanding operation and ancillary services provision from DR generation units, as well as the quantification of the required volume of these services; regulatory studies to identify policies that may promote the deployment of DR.

Following the changes discussed above, power systems, are already considered to be one of the most complex systems built by humans, will become even more complex and more difficult to control and operate in the future. They will include a significant amount of non-conventional, generation (*i.e.*, non-synchronous generators) whose power output will generally be stochastic and greatly dependent on environmental conditions. This is particularly the case in wind, photovoltaic and combined heat and power generation. In addition to those new types of generators, proliferation of power electronic devices, either as an essential, constitutive part of new generator types, power electronic interfaces used to connect variable output (*e.g.*, doubly fed induction generators, full converter connected synchronous or induction wind generators) or essentially DC generation (*e.g.*, photovoltaics) to AC grid, or in the form of stand alone control devices, will further increase the complexity and versatility of the system.

One of the basic challenges facing control and operation of future power systems is development of non-deterministic, *i.e.*, stochastic/probabilistic, methodologies for system analysis to avoid either over conservative or too risky solutions. Deterministic approaches, based on maximum, minimum or selected subset of conditions only, cannot deal successfully with the intermittent, stochastic nature of RES and the requirement to process quickly and efficiently thousands of possible scenarios that may occur in a highly complex system in order to select the most appropriate control action.

In the rest of this chapter some basic requirements with regard to control of power system oscillations and improvement of power quality will be reviewed.

2.2.2 Damping of the System Oscillations

Power system stability is defined as "*the property of a power system that enables it to remain in a state of operating equilibrium under normal conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance*" [25]. It is essential to the performance of a power network. As the complexity of the network increases, the task of maintaining system stability increases as well. In the re-regulated framework with an increased number of non-conventional generators, high proliferation of power electronic devices and demands for power transfers dictated by market rules, the system is foreseen to become more stressed and pushed to operate closer to the stability limits.

Power system stability is broadly sub-divided into rotor angle stability and voltage stability. The former is (or at least used to be) more, if not exclusively, an issue for transmission network operation while the latter was predominantly a "*local issue", i.e.*, typically confined to distribution networks. With new structure and operational requirements of power networks of the future, the above distinction will start to become more and more blurred and rotor angle stability studies will proliferate to lover voltage levels, *i.e.*, to distribution networks. Rotor angle stability involves the ability of the system to remain in synchronism as a whole, even after experiencing a disturbance. As power systems rely largely, and will continue to do so for the foreseeable future, on synchronous machines for electrical power generation, there is an issue of maintaining synchronism of interconnected generators. Voltage stability refers to the ability of the system to maintain voltage of all buses within statutory limits (usually within ±10% of the nominal) under both normal operating conditions and following a disturbance. The essential requirement for preventing voltage instability (and ultimately voltage collapse and wide-spread system blackouts) is to provide adequate reactive power support in the network and proper coordination between voltage regulating devices (e.*g*., tap changing transformers, active and passive shunt or series connected voltage support devices, *etc.*). For low voltage networks with more resistive transmission lines and cables (high resistance to reactance ratios) a reactive support alone may not be sufficient and real power support is required as well. Networks with stochastically varying DR and large numbers of power electronics based control devices (or generator interfaces) will impose more demanding voltage control methodologies.

The focus of this chapter is on rotor angle stability which is further classified into transient or large disturbance stability, and small disturbance stability. Transient stability is the ability of the system to remain in synchronism after being subjected to a large disturbance (*e.g.*, a three-phase fault at any bus) while small disturbance stability is the ability of the system to remain in synchronism following a small disturbances (*e.g.*, naturally occurring, scheduled, load or generation changes, *etc.*). For both of those types of stability the damping of electromechanical oscillations in the system is essential. The physical insight in to the phenomenon of electromechanical oscillations is given in [26] through the concept of damping and synchronizing torque.

As the name suggests, these oscillations occurs as a result of interactions between the electrical and mechanical processes in the power system, namely the conversion between mechanical power (governor and turbine) into electrical power (generator). They are characterized by changes in generator rotor speed on one hand (hence "*mechanical*" in their name) and consequent fluctuations in generated electrical power (hence "*electro*" in their name) on the other. These oscillations are inherent to the synchronous machine. The equation of motion of the rotor of synchronous machine, commonly referred to as the swing equation, is given by [25, 27]

$$T_m - T_e = 2H\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} \tag{2.54}$$

where $T_e = T(\delta, V)$.

Parameters T_m and T_e refer to the mechanical and electrical torque respectively, H is the moment of inertia of the machine, D is the damping constant, V is voltage, K is a constant and δ is the rotor angle.

Considering only small disturbances (see Equation 2.54), these can be literalized about a given equilibrium point yielding

$$\Delta T_m = 2H\frac{d^2\Delta\delta}{dt^2} + D\frac{d\Delta\delta}{dt} + K\cos\delta_o\Delta\delta \tag{2.55}$$

Solving the differential Equation 2.55 for rotor angle gives

$$\Delta\delta = \frac{\Delta T_m}{K\cos\delta_0}\left[1 - e^{-\left(\frac{D}{4H}\right)t}\sin(\omega t + \phi)\right] \tag{2.56}$$

where the frequency of the oscillation, ω is given by

$$\omega = \sqrt{\frac{K\cos\delta_o}{2H} - \left(\frac{D}{4H}\right)^2} \tag{2.57}$$

From the equations above it is obvious that, following a disturbance, the rotor angle will experience oscillatory motion with a frequency given by Equation 2.57. Taking into account generic parameters of generators and substituting the values into the equations above, the frequency range of the power system electromechanical oscillations will typically be within the range of 0.1 – 2.5 Hz [26, 27].

Electromechanical oscillations can be initiated by small disturbances occurring almost continually in the system. A system with unstable electromechanical oscillations would not be possible to operate as the response to any disturbance would result in oscillations with increasing magnitude that would lead to triggering protection and disconnection of the generator from the system. Oscillatory modes that are localized at the individual machines are referred to as local modes. They tend to occupy the higher end of the frequency range for electromechanical modes; *i.e.*, the range from 0.7 to 2.0 Hz [25, 28]. These modes tend to involve only a small part of the system and are usually associated with the angle oscillations of a single machine or oscillations of the single plant against the rest of the system [25]. Modes that are typically far less damped typically involve large groups of generators or plants and have the typical frequency range of 0.2 to 0.8 Hz [29]. They result from the interchange of power across transmission corridors (lines) between generating units in different parts of the system and involve groups of machines in one part of the network oscillating against groups of machines in other parts of the network. Inter-area oscillations have been observed in many power systems around the world over the last few decades and were typically associated with large power transfers across week transmission lines. The unstable electromechanical oscillations can cause massive disruptions to the network and ultimately blackouts [30]. They can also can cause fatigue to the machine shafts, added wear and tear of mechanical actuators of the machine controllers leading to early replacements or breakdowns the costly components. Oscillatory behavior in the network also limits power transfer capacity of tie-lines [29, 31]. To summarize, electromechanical oscillations have significant impacts on the system performance and they need to be well damped in order to insure proper system operation. Appropriate damping of electromechanical oscillations is typically achieved by installing damping controllers in the system. They can be designed and connected as local controllers, *i.e.*, as part of the generator excitation system (the most common of those is the Power System Stabilizer) or as additional damping controllers in control loops of FACTS devices connected to non-generation buses in the network. The latter are typically used for damping of system-wide, *i.e.*, inter-area oscillations.

Locally Installed Damping Controllers

By far the most widely used damping controller in the power system is the Power System Stabilizer. It uses local signals (typically speed, electrical power or frequency) available at generator terminals and injects damping signals (derived based on principle of damping and synchronizing torque [26]) directly into the generator excitation loop. The damping torque provided by PSS is in phase with generator rotor speed deviation and as such directly adds to the system damping torque [25, 26, 32]. PSS usually consists of a series (up to three or four) of tunable cascaded lead-lag compensators (blocks), and low and high frequency filters (to prevent negative interactions outside the target frequency range, *i.e.*, 0.1 to 2.5 Hz) with pre set parameters, though other types of PSSs have been developed over the years [33, 34].

Damping Controllers in Control Loops of FACTS Devices

FACTS devices were originally designed in the 1980s [35] to provide flexible control and operation of the transmission system, *i.e.*, to improve power transfer capability and to restrict or redirect the power flow in the system to designated transmission corridors [36]. They can be split broadly into two main groups, one that redirects the power flow through the control of reactances in the network and the other that uses static converters as voltage sources to inject or absorb power as appropriate. The first group includes devices such as Static Var Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC) and Thyristor Controlled Phase-Shifter (TCPS). The second group includes Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC) and the Interline Power Flow Controller (IPFC). More details about FACTS devices can be found in [35].

At the later stages it was realized that FACTS devices also have a positive impact on damping of electromechanical oscillations (inter-area modes in particular [31]) and ever since there has been huge interest in designing supplementary damping controllers for FACTS devices [35–54].

Design of Damping Controllers

Design and tuning of power system controllers has been a research topic for many years. Many different methods have been proposed [32, 39, 40, 55–65] ranging from classical linear control system theories based on residues and frequency responses to more complex theories such as, Linear Matrix Inequalities (LMI), Multivariable Control and Linear Optimal Control (LOC). While classical methods generally suffer from lack of robustness of the solution, the advanced methods usually require either the oversimplification of the power system model or result in very complex structures of the proposed controllers. Power system engineers, however, overwhelmingly favor classical tuning methods due to their simplicity. Classical tuning methods of damping controllers (*i.e.*, PSSs) can be generally subdivided into three categories: tuning based on the torque-angle loop [32, 66, 67], tuning based on the power-voltage reference loop [45, 55, 68] and tuning based on the exciter control loop [56, 57, 69].

Even though in the vast majority of cases in realistic power systems, locally tuned damping controllers (PSSs) achieved the initially set objective of successful damping of electromechanical oscillations, it has been noted that in order to achieve optimal performance of the system the interactions between different controllers have to be taken into account [70]. This resulted in requirement for coordinated tuning of different controllers in order to enhance the operation of the system as a whole. Coordinated tuning of different controllers is typically performed using optimization methods and techniques. Methods ranging from linear programming to non-linear constrained optimization have been developed in the past [71, 72]. Depending on the formulation of the objective function to be optimized, different optimization routines should be used [37, 73–77]. In most cases the objective function is based on frequency domain information such as eigenvalues and damping factors. Other forms of objective functions, *e.g.*, using controller gain [78] or the phase and gain margin of a specific control loop [79] have also been effective. In addition to these more conventional, analytical optimization methods, more recently optimization has also been performed using evolutionary programming methods such as Genetic Algorithm, Tabu search, Simulated Annealing and Particle Swarm Optimization [80]. These novel optimization methods are particularly suited to complex non-linear systems and have been successfully applied to coordinate multiple controllers in the power system [27, 81–87].

2.2.3 Power Quality Control

The phrase Power Quality appeared as such only in the early to mid- 1980s. Prior to that, all individual phenomena coming under this generic name, voltage sags (dips), harmonics, voltage transients, voltage regulation, voltage flicker and reliability, were studied and referred to separately. Today, Power Quality is an expression used to describe broadly the entire scope of the complex interaction among electrical producers and suppliers, the environment, the systems and devices supplied by the electrical energy and the users of those systems and devices. It generally involves the maintainability of the power delivered, the design, selection, and the installation of every piece of equipment, whether hardware or software in the electrical energy system. It covers all areas from the generation plant to the last customer in the chain of electricity supply and is a measure of how the elements affect the system as a whole.

From the very beginning of generation transmission, distribution and use of electricity, the requirements for continuous delivery of the "*clean*" electrical energy and the efficient and comfortable use of all electrical equipment were, and still are, primary objectives of all electrical power systems [88]. The supply voltage, as a system-wide characteristic, and current as a more local property of the system were required to have: constant sine wave shape with fundamental frequency only, that they are supplied at constant frequency, that they form a symmetrical three-phase power system and have constant RMS value, unchanged over time, that the voltage is unaffected by load changes and that the supply is reliable, *i.e.*, the energy is available when required. Only under these conditions is the quality of electricity supply considered to be good enough. The main types of equipment served by the power supply did not changed dramatically. From the very beginning of the use of electricity, these were, and still are, light sources, motors and heaters/coolers. Further, almost all power quality disturbances that are of interest now have been an intrinsic feature of power supply systems since the earliest times. Finally, electrical systems, devices and controls for generation, transmission and distribution of electricity have evolved over the years and they are certainly more efficient and reliable today than they were in the past. What has changed over the years though, is that equipment characteristics and ways of equipment utilization have changed and influenced increase in the awareness about the power quality issues. Once almost harmless and hardly noticeable, power quality disturbances today have become an increasingly trouble some phenomenon, giving rise to intolerable inconvenience and, more importantly, considerable economic losses. Modern high-efficiency and high-intensity discharge light sources are increasingly used instead of simple incandescent lamps. Sophisticated AC and DC adjustable speed drives are now widely used for more precise control of the motors, and complex air-conditioning systems that have superseded traditional resistive heaters.

These modern "*substitutes*" are much more sensitive to various power quality disturbances than their almost insensitive predecessors. Almost all contemporary electronic equipment is sensitive to various power quality disturbances, either due to its own design features or because of the incorporated control and communication features. This step change in the equipment sensitivity to power quality disturbances was initiated by the introduction of semiconductor components in the 1960s and further strengthened by the spread of personal computers in the 1980s. Since that time, heavy dependence of customers on the comfort provided by the electronic and microprocessor-based systems grows at an exponential rate. Introduction of computer networking, mobile and other communication systems in the 1990s also increased both the range and level of exposure and interference of various commercial and industrial processes. Praised for its high efficiency, effects on energy saving and provision of accurate and comfortable control, modern electronic/microprocessor equipment was promoted and installed at a wholesale rate, demonstrating extraordinary diversity of its usage and affecting almost all aspects of life. At the same time, high sensitivity of this equipment to power quality disturbances (especially to short voltage reduction events), and adverse effects resulting from its nature of operation (*e.g.*, harmonic emission, electromagnetic interference, overheating effects, *etc.*) have resulted in increased interest in power quality.

Besides the use of the more susceptible electrical and electronic equipment, changes in modern production concepts also helped in putting power quality at the focus of interest. Modern manufacturing and service industries are characterized by highly automated processes which are more complex and more sensitive to supply disturbances, and production/operation philosophy governed by "*time-is-money*" approach, "*near the peak*" production plant operating conditions and by "*just-in-time*" manufacturing/delivery concepts. Any disruption of operation, service or production is therefore related to substantially higher costs and losses than before. The best indicator of the severity of power quality problems is probably the volume of the related investments. Industrial and commercial customers with continuous production processes or services are nowadays much more willing to invest capital in order to improve the quality of supply and to reduce the costs of power quality disturbances [89–94]. The interest in maintaining "*good*" power quality is even higher in the financial market services (stock exchanges, credit card transactions and on-line banking) and Internet data centres, where loss of information due to service interruption often exceed several thousands of dollars, pounds, euros, yens *etc.* per second of downtime [95]. Semiconductor wafer plants are probably exposed to the highest risk of potential financial losses due to power quality disturbances, as they concentrate enormously expensive facilities and equipment in a small geographic area [96].

The introduction of the electricity market in recent years also contributed very strongly to the increased interest in power quality. Electric power utilities (network operators, transmission and distribution companies, and power suppliers) are faced with re-regulation and opening of the electricity market. Distribution companies are under considerable pressure to improve and guarantee the quality of the service they provide. A failure to deliver electrical energy of an adequate quality to the customers is likely to result in severe financial penalties and affect their ability to gain new and keep existing customers. Their ability to provide the expected level of quality of supplied electricity is further challenged by proliferation of non-conventional, stochastic, renewable generation and power electronic devices in their system. New types of generators typically have variable voltage and power output requiring more sophisticated control. They are often connected to the system through power electronic devices which are both more sensitive to power quality disturbances, and sources of those disturbances (harmonics) themselves. Power electronic devices are not only used for connection and control of renewable generation but also as a constitutive part of other system controllers (FACTS devices, HVDC systems, *etc.*). It is thus essential for the future of these companies to target investments towards the service and network improvements that will be the most effective. Reliability, availability and good overall quality of delivered electrical energy are still the most important aims of power suppliers. The meaning of these supply attributes, however, has changed somewhat over the past decades taking more into account the situations on the customer's side. The standard assessment of "*customer minutes lost*" has a completely different meaning for customers whose processes and equipment are sensitive to power quality disturbances. Thus, reliability and other traditional concepts used for description of supply system performance have to be reformulated and generalized in order to include at least the most important power quality concepts, as they are becoming more and more appreciated as the standard performance criteria of power supply services.

The manufacturers of (sensitive) electrical equipment and power quality mitigation devices have also shown strong interest in understanding, characterization and quantification of power quality problems. They need to know the basic characteristics of the most frequent power quality disturbances in order to design their products to withstand/ride through those disturbances or to mitigate them. Having in mind the costs of mitigation of power quality problems, improvement of equipment immunity and ride-through capabilities at the equipment manufacturing stage is the most cost-effective approach. The developers of the control software for the microprocessor-based equipment too, are also interested in understanding power quality disturbances in order to prevent software-driven equipment disconnections and mal-operation due to the rigid control or protection setting [97].

Power quality disturbances shut down industrial processes and computer systems, causing losses in productivity and materials at a level never encountered before. These disturbances also annoy and inconvenience residential customers who own an increasing array of modern electronic equipment and find such problems less acceptable in the electricity supply industry that is privately owned and operates in a competitive environment. Regarding the frequency of occurrences and associated costs, voltage sags and short interruptions and harmonics are the two most detrimental power quality disturbances (*e.g.*, [98]).

Power system harmonics are another important power quality phenomenon, which attracts significant attention due their high potential impact on system and equipment operation and performance.

Voltage Sags and Harmonics

Voltage sag (dip) is defined as a decrease in the Root-Mean-Square (RMS) value of an AC voltage between 0.1 p.u. and 0.9 p.u. at power frequency for a duration from 0.5 cycles (10 ms in 50 Hz supply system) to 1 min [99–101]. The magnitude and the duration of a sag have been extensively used for development of equipment compatibility charts and indices and characterization of system sag performance. They are identified as the main characteristics of a voltage sag [102]. Other voltage sag characteristics, *i.e.*, phase angle jump, three-phase unbalance and point on wave of sag initiation and recovery, though very important for assessing equipment sensitivity to voltage sags, received much less attention. Voltage sags are mainly caused by power system faults on transmission or distribution systems, though the faults within an industrial facility, or starting of large induction motors, can also cause voltage sags. As a result of voltage sags at the point of connection, the equipment may trip or fail to perform the intended operation. Examples include: unwanted tripping of sensitive controls; dropping out of AC contactors, personal computers, inverters, variable speed drives, programmable logic controllers; slowing down of induction motors; disconnection of high-intensity discharge lighting, *etc.* As a consequence of individual equipment failure, the whole production process (or service) controlled by that equipment may be interrupted and thus cause significant financial losses to the owner.

Power system harmonics are sinusoidal voltages or currents with a frequencies which are the integer multiple of the frequency at which the supply system is designed to operate (50 or 60 Hz). Harmonics are generated by the whole range of non-linear/harmonic loads where the relationship between voltage and current at every instant of time is not constant, *i.e.*, the load is non-linear. The non-linear currents flowing through the system impedance result in harmonic voltages at the load. Harmonic sources can be broadly classified as:

- Saturable devices where the source of non-linearities is the physical characteristics of the iron core. They include transformers, rotating machines, non-linear reactors, *etc.*;
- Arcing devices where the source of non-linearities is the physical characteristics of the electric arc. They include arc furnaces, arc welders and fluorescent lighting;
- Power electronics where the source of non-linearities is semiconductor device switching which occurs within a single cycle of the power system fundamental frequency. They include Variable Speed Drives (VSD), DC motor drives, electronic power supplies, rectifiers, inverters, FACTS devices, HVDC transmission systems, *etc*.

The principle measure of the effective (RMS) value of harmonic distortion is defined as Total Harmonic Distortion (THD) and is given by

$$THD_M = \frac{\sqrt{\sum_{h=2}^{h_{\max}} M_h^2}}{M_1} \tag{2.58}$$

where h is harmonic order and M is RMS value of the individual current or voltage harmonic.

However, current distortion levels characterized by THDI can be misleading when the fundamental current is low. The impact of a high THDI value on the system for light load is insignificant, since the magnitude of harmonic currents is low even though its relative distortion to the fundamental frequency is high. Hence, another distortion index known as the Total Demand Distortion (TDD) [103–105] is often used to indicate a more realistic impact of harmonic current distortion on the system

$$TDD_I = \frac{\sqrt{\sum_{h=2}^{h_{\max}} I_h^2}}{I_L} \tag{2.59}$$

where I_L is the maximum demand load current (15 or 30 min demand) at fundamental frequency at the Point of Common Coupling (PCC), calculated as the average current of the maximum demands for the previous 12 months [104].

Besides THD and TDD, several other indices specific to the type of equipment affected by harmonics, particularly telecommunication and audio system are available [106, 107].

The overall magnitude of harmonic currents in a distribution network typically follows the trend of fundamental current (*i.e.*, power demand), as harmonic (non-linear) and linear loads tend to be simultaneously present in the network, particularly commercial loads, which operate over distinct periods of time. In most cases, in the short term, an upward trend in power demand is likely to be followed by a similar upward trend in magnitude of harmonic currents [108–111]. In addition, harmonic distortion in distribution networks is influenced by load composition. For example, a distribution feeder that supplies 100% industrial load is likely to have different harmonic distortion levels from a feeder that supplies 40% commercial and 60% residential load [108]. The difference arises due to the characteristics of harmonic loads in each case which, besides different THD level, also produce different characteristic harmonics. Large power VSD and converters used in industrial environment generate predominantly 5th and 7th harmonics, due to the use of six pulse converters (dominant harmonics produced by n-pulse converter are typically $n\pm1$). Single-phase power electronic devices, used in commercial and residential loads, on the other hand generate predominantly 3rd, 5th and 7th harmonics. As far as variation in THD with time is concerned, distribution feeders dominated by residential loads are likely to experience an increase in magnitude of harmonic currents during the night when television and lights are switched on. Feeders supplying predominantly commercial loads typically experience decrease in magnitude of harmonic currents during late night periods when premises are closed for business.

With the rapid development of electronic, information and communication technology, usage of non-linear/harmonic loads is expected to increase at both system and end user level, and so does the level of voltage distortion in power systems. In commercial and residential buildings, single phase non-linear/harmonic loads are already being used in large quantities (personal computers, fluorescent lighting, office equipment, *etc.*). It is envisaged that higher power non-linear devices such as central airconditioning with variable speed drives will increasingly find their way into customer loads in the near future. At the system level, power electronic interfaces employed for connection and control of renewable generation, FACTS devices that are increasingly employed for efficient control of power networks and HVDC transmission systems used for bulk power transfer across long distances may contribute further to the overall harmonic pollution of the network. From the utility viewpoint, high harmonic distortion increases the risk of customer complaints as a result of equipment malfunction, and in extreme cases power shut down. In addition, harmonic distortion increases the volt-ampere demand on transformers and lines/cables through additional heat loss, which decreases the margin on the entire power distribution system and the opportunity to add more customers on existing systems. Customers, on the other hand, are inclined to use non-linear loads due to their state-of-the-art technology, but are reluctant to invest in harmonic mitigation devices, particularly those from the commercial and residential sectors. The major effects of voltage and current harmonic distortion can be classified as follows:

- Thermal stress, through increasing copper, iron and dielectric losses;
- Insulation stress, through the increase of peak voltage, *i.e.*, voltage crest factor;
- Load disruption.

Since the major effects of harmonic distortion typically have cumulative effect, *i.e.*, overheating and insulation fatigue, they depend on the level of THD and duration of the state in which this increased THD exists. Because of that, harmonic resonance [104], either parallel or series, contributes significantly to the ultimate effect of harmonics on equipment and network. During the resonant condition in the network, critical harmonic is particularly magnified, resulting in high voltages and currents which can contribute to excessive heating of the device, insulation breakdown or load/process interruption. A major cause of resonant condition in the network is the installation of inadequately sized Power Factor Correction Capacitors (PFCC) which brings natural resonant frequency down to the level of 5th (250 Hz) or 7th (350 Hz) harmonic.

Realizing the potential magnitude of losses due to power quality disturbances [112–126], more and more industrial and commercial customers have started to seek protection, both technical and contractual, from the impact of power quality disturbances. The most common approach is to install mitigation devices (custom power) to reduce the number of disruptive events. Others go for higher quality of supply through power quality contracts with the electrical utility. However, regardless of which option is preferred, the investment must be economically justifiable.

From the electrical utilities' point of view, reducing the number of voltage sags and short interruptions and controlling harmonic levels in the network would boost customer satisfaction and improve future business prospects. In today's competitive electrical market, the standard of power quality has to be constantly upgraded to ensure business survival.

Controlling Voltage Sags

In order to reduce potential financial losses arising from voltage disturbances, voltage sags in particular, several options could be adopted. The first certainly would be to reduce the causes of disturbances. Since power system faults are the major cause of voltage sags, action can be taken by transmission and distribution companies to reduce the occurrences of faults. This includes, at transmission system level, adjusting transmission tower footing resistance, installing line arresters, regular insulator washing, installing fast switches with instantaneous protection systems and arc-suppression coil earthing with time grading protection. At the distribution level these action include regular tree trimming, installing animal guards, installing arresters, loop schemes, *i.e.*, meshed rather than radial network topology, modified feeder designs and modified protection co-ordination. Even though these preventive measures could significantly reduce the occurrence of faults, and ultimately voltage sags, they could not be completely removed. Therefore, further measures should be taken to deal with remaining faults and to insure that equipment rides through disturbances. At the utility level, FACTS based conditioning devices can be used including Dynamic Voltage Restorer (DVR), Solid State Transfer Switch (SSTS), STATCOM, SSSC, SVC, UPFC. The problem with wide application of these devices, however, is very often their excessive cost. So very careful techno-economic assessment of possible mitigation options has to be carried out prior to proposing a final solution. Bearing in mind the power level involved, *i.e.*, protecting the whole feeder or part of the network, and resulting cost of mitigating device and the fact that not all customers are equally sensitive to voltage disturbances, it is often (if not always) much more economically justifiable to protect only customers plant or selected feeders. At this level, similar mitigation devices can be used as before (*e.g.*, DVR, SSTS, STATCOM, *etc.*); however, due to the much lower rating of protected loads, the cost of solution would be much lower. In addition to these, some other devices and techniques could be used since the powers involved are smaller. These include flywheels, Superconducting Magnetic Energy Storage (SMES), Magnetic Synthesizers, on-line or rotary UPS, Motor Generator (MG) sets, private generation, static and active voltage conditioners, electronic tap changers and even constant voltage transformers (for smaller static/fixed loads). If, however, as often is the case, only particular equipment or devices have to protected and quite often its control system, then smaller ratings and simpler devices can be used. For protecting control systems, devices such as constant voltage (ferro resonant) transformers, UPSs, SMES and MG sets can be used. Individual loads can be protected by improved design for voltage tolerance (including internal control algorithms and protection settings), improved starters, improved DC supplies (larger capacitors to insure adequate level of DC voltage), lower drop-out characteristics or again using similar lower rated devices as for protection of control circuits, *e.g.*, constant voltage (ferro-resonant) transformers. The cost of mitigation typically increase exponentially as the solution is applied to higher voltage level and as it involves more than one device or one control circuit (due to the rating of mitigation device required). It has to be pointed out though that even though modern CUPS (*e.g.*, DVR, STATCONM, UPFC, *etc.*), whose origin is in FACTS technology and which can synthesize required missing voltage and almost fully compensate for the disturbance and as such provide very good if not excellent protection of equipment and processes, may not always be economically the best solution due to their very high costs. In many practical cases a simple modification of control algorithms, improved design of the equipment or use of simple device such as constant voltage transformer can significantly reduce the number of process interruptions and consequently financial losses incurred to end use customers. In cases when this is not possible, however, more sophisticated and more expensive solutions have to be sought and careful techno-economic consideration is required. In such cases, additional benefits (voltage regulation, power factor correction, voltage and angular stability protection provided to other buses/customers in the network, *etc.*) that may arise from the application of sophisticated mitigation device have to taken into account when deciding on its techno-economic merits.

Controlling Harmonic

Harmonic currents typically go through various stages of attenuation before they reach the utility source. One of the common, naturally occurring phenomena is the cancelation of harmonic currents due to diversity in phase angles resulting from different load mix and operating conditions. Others include deliberate supply/connection of loads through transformers having different winding connections (*e.g.*, one VSD supplied through delta/delta transformer and the other through delta/wye transformer) as these introduce additional phase shift which then enhances harmonic cancelation. Addition of small inductors (chokes), typically rated at about 3% of the drive rating, in variable speed drives further contributes to reduction in harmonic currents flowing in the network.

The best, and often the cheapest, way of solving harmonic problems is at the source through equipment specification and design. This includes use of Pulse Width Modulation (PWM) switching techniques (standard practice in modern VSDs and inverter technologies) resulting in much less distorted current and voltage waveforms, choke inductance built in VSDs (which can half the THD with moderate, about 20%, increase in cost), use of 12 or 24 pulse inverters instead of 6 pulse inverters and reducing the overall THD and in particular the content of critical 5th and 7th harmonic, installation of PFCC whose size is less then 20% of the rating of supply transformer, or if larger size is needed, use tuned capacitor banks, *etc.* In case of synchronous machines as harmonic sources, appropriate winding pitch should be used to reduce harmonic content in output voltage and current (*e.g.*, 2/3 winding pitch minimizes 3rd harmonic component).

One of the common harmonic problems in commercial facilities is in-crease in neutral conductor currents. Those currents, which should ideally be zero in balanced, symmetrical and non-distorted systems, could rise to unacceptably high levels due to high 3rd harmonic component in particular (triplen harmonic currents, 3rd, 9th, 15th, *etc.*, coming from different phase conductors do not cancel in a neutral conductor as do fundamental currents). In situations like that the size of the neutral conductor should be increased (at least to the same size as phase conductors or double the size of phase conductor) to prevent overheating or 3rd harmonic filter installed at each load or in neutral conductor. Zig-zag transformers are also often used in cases like this as they provide low impedance path for 3rd harmonic current (and high impedance path to positive sequence current so the load is not affected) and it gets trapped inside transformer.

If, however, the required reduction in THD cannot be achieved in one of the above ways, or through a combination of those, than harmonic filters (passive or active) need to be installed.

Passive filters are an economical method for mitigation of harmonic currents in distribution network [127–129]. In addition to filtering harmonic currents, they can also be used as a reactive power source. Ideally, passive filters should be placed at the point of common coupling by the respective customer, so that harmonic currents penetration to utility system is kept at the minimum level. However, there are also cases where distribution feeders carry a significant amount of harmonic currents, resulting in unacceptable harmonic voltage distortion at network buses, so filters should installed at all strategic network buses.

A passive harmonic filter is cheap as it is built from passive network elements, *i.e.*, resistors, inductors and capacitors. There are two approaches to suppress undesired harmonic currents using passive filters. The series harmonic filter uses series impedance to block harmonic currents while the shunt filter act as harmonic current sink and diverts harmonic currents by providing low impedance shunt path [128]. Series filters are more expensive (and therefore less frequently used) than shunt filters as they must carry full load current. Three types of shunt filters, namely, single-tuned first order, high-pass second-order, and double band pass (double-tuned) filters are most commonly used. The function of passive shunt harmonic filters is usually two-fold to supply the necessary reactive power and to divert harmonic currents by providing a low impedance path at the tuned frequency. Hence, the major criterion of harmonic filter design is to select suitable capacitor size that results in desired power factor at fundamental frequency. The harmonic filter is then tuned by selecting appropriate values of inductances and resistances that result in the filter effectively diverting all or part of the specified harmonic currents. The reactance of the inductance is typically tuned based on the reactance of capacitor corresponding to the reactive power requirement and tuned harmonic order of the filter. The resistance is determined based on the desired quality factor (measure of the sharpness of the tuning frequency) of the filter. Although the common practice is to limit the resistance of the filter to the reactor's resistance, external resistance is often added to modify the sharpness of tuning or change the bandwidth of the impedance *vs* frequency [128]. The single-tuned filter is the most frequently used filter as it is the simplest and the cheapest [128, 129]. It consists of a series combination of a capacitor, inductor and resistor and it is typically tuned to low harmonic frequencies. The main advantage of the high pass second order filter is that it provides low impedance for a wide range of frequencies [129] when tuned to a low Q-factor of between 0.5 and 5. However, one of its disadvantages is that its minimum impedance is never as low as that of the single-tuned filter [130], and therefore it is not as effective in diverting harmonic currents. The double tuned band pass filter consists of a series combination of a main capacitor and reactor, and a tuning device, which is a tuning capacitor connected in parallel with a tuning reactor. The reactances of both, the series and parallel circuit, are tuned to the mean geometric frequency of two specific harmonic frequencies that are to be controlled. It is in general very effective in diverting harmonic currents of two specific frequencies, particularly when tuned to a higher Q-factor (between 5 and 10). Finally, harmonic filters that are tuned to frequencies slightly lower than the resonant frequency, so that the minimum impedance does not occur at the exact order of harmonic, are referred to as detuned filters. They are cheaper as current ratings of their components could be reduced accordingly. In addition, dielectric materials of capacitors typically degrade over time and therefore it is necessary to compensate for this phenomenon by tuning the filter to a lower resonant frequency [129].

The second, more expensive, option of filtering harmonics is to apply active harmonic filters. They are connected in shunt and handle lower currents (typically only the distorted component of total load current) and therefore cannot be overloaded. They are typically of smaller size (up to about 150 kVA) than passive filters and installed close to the harmonic source. Active filters are power electronic based devices, similar to inverters, which first measure/detect harmonic content in load current and then synthesize, through appropriate switching, a signal that negates the harmonic currents injected by the non-linear loads connected to them. When injected back into the network this signal virtually eliminates harmonics from the load current and the combination of the active filter and non-linear load looks like a resistive load to the power system with low distortion and unity power factor. Active harmonic filters can be incorporated as an active front end of VSDs and as such eliminate almost completely harmonic distortion resulting from VSD operation. The cost of VSD with an active front end that acts as a harmonic filter, however, is about double the cost of passive front end VSD.

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