Conclusions

The matrix converter topology has been known for more than twenty years and since then it appeared as an attractive solution for adjustable speed drive applications. The matrix converter is a direct AC/AC converter which performs the AC /AC power conversion in a single step and not via a DC link as in traditional indirect converters. It consists of 9 bi-directional switches that allow any output phase to be connected to any input phase.

The matrix converter has several advantages over traditional rectifier-inverter type power converters. It provides sinusoidal input and output waveforms with neither low order harmoics nor subharmonics. It has inherent bi-directional energy flow capability and the input power factor can be fully controlled. Moreover, due to the lack of the DC link it allows to get rid of the relevant bulky and lifetime-limited energy-storing capacitors. However, the matrix converter can not be defined as an “all silicon” converter solution since some energy storage requirements are imposed by the current filter which is needed at the input in order to prevent the converter input current switching harmonics from flowing onto theAC mains.

A theoretical limit of the the matrix converter is the reduced input-to-output voltage transfer ratio, which is set to 0.866 under the constraint of sinusoidal input and output waveforms. But it has not been due to this voltage limit if the matrix converter technology have taken more than twenty years for appearing on the adjustable speed drives market. The delay was mainly due to several practical obstacles related to the matrix converter control complexity and much more to the implementation of the bi-directional switches, which rises a series of problems related to commutation and protection of the bi-directional switches.

The scope of the work presented in this thesis has been to investigate the matrix converter as alternative to indirect power converters in adjustable speed drives. The focus of the research activity has been directed to control algorithms and commutation strategies.

With regard to the control algorithms three different strategies based on the space vector modulation technique has been considered. For each strategy a theoretical analysis supported by numerical simulations have carried out. Particular attention has been given to the performance under non ideal input supply voltage conditions. It should be noted that matrix converters, due to the absence of the DC link capacitors, are sensitive to input voltage disturbances, as they are directly transmitted to the output if not properly compensated. Since, real system are always unbalanced to a certain extent and distorted by non linear loads, the capability to compensate for input voltage disturbances is somehow a mandatory feature for a reliable and effective control algorithm.

Each control strategy has the capability for compensating input voltage disturbance but the input current quality performance are different. These input current performance have been analysed in details. A theoretical analysis along with numerical simulations have represented the preliminay work for a following series of experimental tests which have required the implementation of all three control algorithm on a matrix converter prototype. This represented an important part of the activity carried out. The experimental results obtained for the three strategies showed the validity of the theoretical input current analysis and confirmed the numerical results. On the basis of the results achieved two papers have been presented at international conferences and published in the relevant proceedings.

Within the ambit of the matrix converter control algorithms it has been also investigated a new control method which allows the use of matrix converter in direct torque control of induction machine. Even in this case a preliminary work of analysis has been carried out by means of a mathematical model of the investigated drive system and numerical simulations. Afterwards the control method has been implemented on drive system prototype. The experimental results showed that the matrix converter performance are good on the output motor side but poor on the input side with regard to the input line current harmonic distortion. But a detailed analysis has shown that such poor performance was due to the high sampling frequency used in the experimental implementation. On the basis of the analysis carried out an original modified control algorithm has been proposed. This modified control algortim allows to reduce the input line current hamonic distortion without negatively affect the output motor side performance. The performance of such algorithm has been verified by numerical simulations. The experimental results as well as the modified control algorithm have been proposed in a paper published in the proceedings of an international conference.

As far as the commutation strategies is concerned most of the today available commutation strategies have been thoroughly investigated and reviewed. All strategies rely on the possibility to selectively enable the conduction of the positive and negative output current polarity. Therefore, these strategies have to be intended only for bi-directional switches implemented by an antiparallel arrangement of two discrete power semiconductor devices with series diode.

In order to safely commutate the load current between two bi-directional switches it is mandatory some knowledge of the commutation conditions: the voltage across the commutating bi-directional switches or the output current must be measured. These information are required in order to determine the proper sequence of switching states combinations that does not lead to the hazard either of a short circuit or of an open circuit. This is the common operating principle of all the commutation strategies.

Then, the strategies differentiate with respect to the number of switching state combinations which makes up a safe commutation sequence and to which information about the commutation process is used: voltage or current. By using most of these commutation strategies the need of snubber networks for bi-directional switches can be eliminated.

An original commutation strategy, named “three-step” has been proposed and implemented on a complex programmable logic device. The advantage of this strategy with respect to the other is that during a commutation process the output current commutate between the switches always at the same instant with respect to the beginning of the process. As a consequence, there is no need for a compensation in order to get the optimum modulation of the input and output quantities. Moreover, with respect to those strategies whose commutation sequence consists of four steps, the proposed strategy carries out a faster commutation. This is a significative improvement from the modulation point of view, because the time needed by the commutation process imposes the minimum time interval that the modulator is capable to apply. In other words it can be said that a faster commutation process imply a higher resolution of the modulation.

On the basis of the activity carried out and the results achieved with regard to the matrix converters control algorithms and commutation strategies, and looking at the state of the art, the event of a matrix converter technology break through into the series production seems to approaching fastly, since all the traditional practical problems related to its realization have found reliable, efficient and costly effective solution.

Elenco Equazioni

$$\bar{x} = x_d + j\,x_q = \frac{2}{3}(\,x_a + \bar{a}\,x_b + \bar{a}^2\,x_c\,) \qquad (4.1)$$

where $\bar{a} = e^{j\frac{2\pi}{3}}$.

$$x_a = \bar{x} \cdot 1, \qquad x_b = \bar{x} \cdot \bar{a}, \qquad x_c = \bar{x} \cdot \bar{a}^2 \qquad (4.2)$$

$$\bar{x}(t) = \sum_{k=-\infty}^{+\infty} \bar{X}_k\, e^{\,j\,k\,\omega t} \qquad (4.3)$$

$$\bar{X}_k = \frac{1}{T}\int_0^T \bar{x}(t)\, e^{-j\,k\,\omega t}\, dt \qquad k = 0, \pm 1, \pm 2, \ldots, \infty \qquad (4.4)$$

$$\begin{aligned} \bar{X}_1 &= \bar{X}_p \\ \bar{X}_{-1} &= \bar{X}_n^* \end{aligned} \qquad (4.5)$$

$$\left.\begin{aligned} x_1 &= X_{max}\,cos\left(w\,t + \vartheta_i\right) \\ x_2 &= X_{max}\,cos\left(w\,t + \vartheta_i - \tfrac{2\pi}{3}\right) \\ x_3 &= X_{max}\,cos\left(w\,t + \vartheta_i - \tfrac{4\pi}{3}\right) \end{aligned}\right\} \qquad (4.6)$$

$$\bar{x} = X_{max}\, e^{\,j\,\vartheta_i}\; e^{\,j\,w\,t} = \bar{X}\, e^{\,j\,w\,t} \qquad (4.7)$$

$$\bar{x} = \bar{X}_1\, e^{\,j\,w\,t} + \bar{X}_{-1}\, e^{-j\,w\,t} \qquad (4.8)$$

$$\bar{x} = \bar{X}_1\, e^{\,j\,w\,t} + \bar{X}_{-5}\, e^{-j\,5\,w\,t} \qquad (4.9)$$

$$\bar{v}_i = \frac{2}{3}(\,v_{ab} + \bar{a}\,v_{bc} + \bar{a}^2 v_{ca}\,) = v_i(t)\,e^{\,j\,\alpha_i(t)} \qquad (4.10)$$

$$\bar{v}_o = \frac{2}{3}(\,v_{AB} + \bar{a}\,v_{BC} + \bar{a}^2 v_{CA}\,) = v_o(t)\,e^{\,j\,\alpha_o(t)} \qquad (4.11)$$

$$\bar{i}_i = \frac{2}{3}(\,i_a + \bar{a}\,i_b + \bar{a}^2 i_c\,) = i_i(t)\,e^{\,j\,\beta_i(t)} \qquad (4.12)$$

$$\bar{i}_o = \frac{2}{3}(\,i_A + \bar{a}\,i_B + \bar{a}^2 i_C\,) = i_o(t)\,e^{\,j\,\beta_o(t)} \qquad (4.13)$$

$$p = \frac{3}{2} \bar{e} \cdot \bar{i} = p_o \qquad (4.14)$$

$$\bar{e}_i = \frac{1}{\sqrt{3}} \bar{v}_i e^{-j\frac{\pi}{6}} \qquad (4.15)$$

$$\bar{v}_o' = \bar{v}_o^I d^I + \bar{v}_o^{II} d^{II} = \frac{2}{\sqrt{3}} v_o \cos\left(\alpha_o - \tfrac{\pi}{3}\right) e^{j[(K_v - 1)\pi/3 + \pi/6]} \qquad (4.16)$$

$$\bar{v}_o'' = \bar{v}_o^{III} d^{III} + \bar{v}_o^{IV} d^{IV} = \frac{2}{\sqrt{3}} v_o \cos\left(\alpha_o + \tfrac{\pi}{3}\right) e^{j[(K_v - 1)\pi/3 - \pi/6]} \qquad (4.17)$$

$$(\bar{i}_i^I d^I + \bar{i}_i^{II} d^{II}) \bullet j i_i e^{j\beta_i} = 0 \qquad (4.18)$$

$$(\bar{i}_i^{III} d^{III} + \bar{i}_i^{IV} d^{IV}) \bullet j i_i e^{j\beta_i} = 0 \qquad (4.19)$$

$$d^I = \frac{2}{\sqrt{3}} \frac{v_o}{v_i} \frac{\cos\left(\tilde{\alpha}_o - \tfrac{\pi}{3}\right) \cos\left(\tilde{\beta}_i - \tfrac{\pi}{3}\right)}{\cos \varphi_i} \qquad (4.20)$$

$$d^{II} = \frac{2}{\sqrt{3}} \frac{v_o}{v_i} \frac{\cos\left(\tilde{\alpha}_o - \tfrac{\pi}{3}\right) \cos\left(\tilde{\beta}_i + \tfrac{\pi}{3}\right)}{\cos \varphi_i} \qquad (4.21)$$

$$d^{III} = \frac{2}{\sqrt{3}} \frac{v_o}{v_i} \frac{\cos\left(\tilde{\alpha}_o + \tfrac{\pi}{3}\right) \cos\left(\tilde{\beta}_i - \tfrac{\pi}{3}\right)}{\cos \varphi_i} \qquad (4.22)$$

$$d^{IV} = \frac{2}{\sqrt{3}} \frac{v_o}{v_i} \frac{\cos\left(\tilde{\alpha}_o + \tfrac{\pi}{3}\right) \cos\left(\tilde{\beta}_i + \tfrac{\pi}{3}\right)}{\cos \varphi_i} \qquad (4.23)$$

$$-\frac{\pi}{6} < \tilde{\alpha}_o < +\frac{\pi}{6}, \qquad -\frac{\pi}{6} < \tilde{\beta}_i < +\frac{\pi}{6} \qquad (4.24)$$

$$d^I + d^{II} + d^{III} + d^{IV} \leq 1 \qquad (4.25)$$

$$v_o \leq v_i \frac{\sqrt{3}}{2} \frac{|\cos \varphi_i|}{\cos \tilde{\alpha}_o \cos \tilde{\beta}_i} \qquad (4.26)$$

$$V_o \leq V_i \frac{\sqrt{3}}{2} |\cos \varphi_i| \qquad (4.27)$$

$$\frac{3}{2} \bar{e}_i \cdot \bar{i}_i = \frac{3}{2} \bar{e}_o \cdot \bar{i}_o \qquad (4.28)$$

$$\overline{\Psi} \cdot j\,\bar{i}_i = 0 \qquad (4.29)$$

$$\bar{i}_i = \frac{4}{3}\frac{p_o}{\bar{e}_i\,\overline{\Psi}^* + \bar{e}_i^{\,*}\,\overline{\Psi}}\overline{\Psi} \qquad (4.30)$$

$$p_o = \frac{3}{2}\,\bar{e}_o \cdot \bar{i}_o \qquad (4.31)$$

$$\overline{\Psi} = \bar{e}_i \qquad (4.32)$$

$$\bar{i}_i = \frac{2\,P_o}{3\,\bar{e}_i^*} \qquad (4.33)$$

$$\bar{e}_i = \overline{E}_{i_1} e^{j\omega_i t} + \Delta\bar{e}_i \qquad (4.34)$$

$$\bar{i}_i = \frac{2P_o}{3\overline{E}_{i_1}^*} e^{j\omega_i t} + \Delta\bar{i}_i \qquad (4.35)$$

$$\overline{\Psi} = \overline{E}_{i_1} e^{j\omega_i t} + \Delta\overline{\Psi} \qquad (4.36)$$

$$\bar{i}_i = \frac{2P_o}{3\overline{E}_{i_1}^*} e^{j\omega_i t} + \frac{P_o}{3\left|\overline{E}_{i_1}\right|^2}\left(\Delta\overline{\Psi} - \Delta\bar{e}_i\right) - \frac{P_o}{3\overline{E}_{i_1}^{*\,2}} e^{j2\omega_i t}\left(\Delta\overline{\Psi}^* + \Delta\bar{e}_i^{\,*}\right) \qquad (4.37)$$

$$\Delta\bar{e}_i = \sum_{-\infty}^{+\infty}{}_{k\neq 1}\ \Delta\overline{E}_{ik}\ e^{j\,k\,\omega_i\,t} \qquad (4.38)$$

$$\Delta\bar{i}_i = \sum_{-\infty}^{+\infty}{}_{k}\ \Delta\bar{I}_{ik}\ e^{j\,k\,\omega_i\,t}$$

$$\Delta\overline{\Psi} = \Delta\bar{e}_i \qquad (4.39)$$

$$\overline{\Psi} = \bar{e}_i \qquad (4.40)$$

$$\bar{i}_i = \frac{2P_o}{3\overline{E}_{i_1}^*} e^{jw_i t} - \frac{2P_o}{3\overline{E}_{i_1}^{*\,2}} \sum_{-\infty}^{+\infty}{}_{k\neq 1}\ \Delta\overline{E}_{ik}^*\ e^{j(2-k)w_i\,t} \qquad (4.41)$$

$$\Delta\overline{\Psi} = -\Delta\overline{e}_i \tag{4.42}$$

$$\overline{\Psi} = \overline{e}_i - 2\Delta\overline{e}_i \tag{4.43}$$

$$\overline{i}_i = \frac{2P_o}{3\overline{E}^*_{i\,1}} e^{\,jw_i t} - \frac{2P_o}{3\left|\overline{E}_{i_1}\right|^2}\sum_{-\infty,\ k\neq 1}^{+\infty} \Delta\overline{E}_{i_k}\, e^{\,j\,k\,w_i t} \tag{4.44}$$

$$\Delta\overline{\Psi} = 0 \tag{4.45}$$

$$\overline{\Psi} = \overline{E}_{i_1} e^{\,j\omega_i t} \tag{4.46}$$

$$\overline{i}_i = \frac{2P_o}{3\overline{E}^*_{i\,1}} e^{\,jw_i t} - \frac{P_o}{3\left|\overline{E}_{i_1}\right|^2}\sum_{-\infty,\ k\neq 1}^{+\infty} \Delta\overline{E}_{i_k} e^{\,j\,k\,w_i t} - \frac{P_o}{3\left|\overline{E}_{i_1}\right|^2}\sum_{-\infty,\ k\neq 1}^{+\infty} \Delta\overline{E}^*_{i_k} e^{\,j\,(\,2-k\,)w_i t} \tag{4.47}$$

$$HD_{15} = \frac{\sqrt{\sum_{k=2}^{15} I_{k\,max}}}{I_{1max}} \tag{4.48}$$

$$I_{i_{RMS}} = \sqrt{\frac{1}{T}\int_0^T (\,i_a^2 + i_b^2 + i_c^2\,)\,dt} \tag{4.49}$$

$$\overline{e}_i = \overline{E}_{i\,1}\, e^{\,j\,\omega_i\,t} + \overline{E}^*_{i-1}\, e^{-\,j\,\omega_i\,t} \tag{4.50}$$

$$\Delta\overline{e}_i = \overline{E}_{i-1}\, e^{-\,j\,\omega_i\,t} \tag{4.51}$$

EQUAZIONI TABLE IV

Strategy A

$$\overline{\Psi} = \overline{E}_{i\,1}\, e^{\,j\,\omega_i\,t} + \overline{E}^*_{i-1}\, e^{-\,j\,\omega_i\,t}$$

$$\overline{i}_i = \frac{2P_o}{3\overline{E}^*_{i\,1}} e^{\,jw_i t} - \frac{2P_o}{3\,\overline{E}^*_{i_1}}\frac{\overline{E}_{i-1}}{\overline{E}_{i_1}} e^{\,j\,3\,w_i t}$$

Strategy B

$$\overline{\Psi} = \overline{E}_{i\,1}\, e^{j\,\omega_i\,t} - \overline{E}^{*}_{i-1}\, e^{-j\,\omega_i\,t}$$

$$\bar{i}_i = \frac{2P_o}{3\overline{E}^{*}_{i\,1}}\, e^{\,jw_i t} - \frac{2P_o}{3\,\overline{E}^{*}_{i_1}}\frac{\overline{E}_{i-1}}{\overline{E}_{i_1}}\, e^{-j\,w_i t}$$

Strategy C

$$\overline{\Psi} = \overline{E}_{i\,1}\, e^{j\,\omega_i\,t}$$

$$\bar{i}_i = \frac{2P_o}{3\overline{E}^{*}_{i\,1}}\, e^{\,jw_i t} - \frac{P_o}{3\,\overline{E}^{*}_{i_1}}\frac{\overline{E}_{i-1}}{\overline{E}_{i_1}}\, e^{-j\,w_i t} - \frac{P_o}{3\,\overline{E}^{*}_{i_1}}\frac{\overline{E}_{i-1}}{\overline{E}_{i_1}}\, e^{j\,3\,w_i t}$$

$$\overline{E}_{i\,1} = 300\,V,\ \ \angle 0^{o} \qquad \overline{E}_{i\,-1} = 30\,V,\ \ \angle 0^{o} \qquad \text{thereof} \qquad u = \frac{\left|\overline{E}_{i\,-1}\right|}{\left|\overline{E}_{i\,1}\right|} = 0.1 \tag{4.52}$$

$$\overline{E}_{i\,1} = 300\,V,\ \ \angle 0^{o} \qquad \overline{E}_{i\,+7} = 15\,V,\ \ \angle 0^{o} \qquad \overline{E}_{i\,-11} = 9\,V,\ \ \angle 0^{o} \tag{4.53}$$

$$\bar{e}_i = \overline{E}_{i\,1}\, e^{j\,\omega_i\,t} + \overline{E}_{i+7}\, e^{\,j\,7\,\omega_i\,t} + \overline{E}_{i-11}\, e^{-j\,11\omega_i\,t} \tag{4.54}$$

$$\Delta\bar{e}_i = \overline{E}_{i+7}\, e^{j\,7\omega_i\,t} + \overline{E}_{i-11}\, e^{-j\,11\omega_i\,t} \tag{4.55}$$

$$d_{+7} = \frac{\left|\overline{E}_{i+7}\right|}{\left|\overline{E}_{i\,1}\right|} = 0.05 \quad , \quad d_{-11} = \frac{\left|\overline{E}_{i\,-11}\right|}{\left|\overline{E}_{i\,1}\right|} = 0.03 \tag{4.56}$$

EQUAZIONI TABLE V

Strategia A

$$\overline{\Psi} = \bar{e}_i$$

$$\bar{i}_i = \frac{2P_o}{3\overline{E}^{*}_{i\,1}}\, e^{\,jw_i t} - \frac{2P_o}{3\,\overline{E}^{*}_{i_1}}\frac{\overline{E}_{i-1}}{\overline{E}^{*}_{i_1}}\, e^{j\,3\,w_i t}$$

Strategia B

$$\overline{\Psi} = \overline{E}_{i\,1}\, e^{j\,\omega_i\, t} - \overline{E}_{i+7}\, e^{j\,7\,\omega_i\, t} - \overline{E}_{i-11}\, e^{-j\,11\,\omega_i\, t}$$

$$\bar{i}_i = \frac{2P_o}{3\overline{E}^*_{i\,1}} e^{\,j w_i t} - \frac{2P_o}{3\,\overline{E}^*_{i_1}} \frac{\overline{E}_{i+7}}{\overline{E}_{i_1}} e^{+j\,7 w_i t} - \frac{2P_o}{3\,\overline{E}^*_{i_1}} \frac{\overline{E}_{i-11}}{\overline{E}_{i_1}} e^{-j 11 w_i t}$$

Strategia C

$$\overline{\Psi} = \overline{E}_{i\,1}\, e^{j\,\omega_i\, t}$$

$$\bar{i}_i = \frac{2P_o}{3\overline{E}^*_{i\,1}} e^{\,j w_i t} - \frac{P_o}{3\overline{E}^*_{i_1}} \frac{\overline{E}_{i+7}}{\overline{E}_{i_1}} e^{-j\,5 w_i t} - \frac{P_o}{3\overline{E}^*_{i_1}} \frac{\overline{E}_{i+7}}{\overline{E}_{i_1}} e^{\,j\,7\, w_i t} - \frac{P_o}{3\overline{E}^*_{i_1}} \frac{\overline{E}_{i-11}}{\overline{E}_{i_1}} e^{-j 11 w_i t} - \frac{P_o}{3\overline{E}^*_{i_1}} \frac{\overline{E}_{i-11}}{\overline{E}_{i_1}} e^{\,j 13\, w_i t}$$

$$\overline{e}_i = \overline{E}_{ip}\, e^{j\,\omega_i\, t} + \overline{E}^*_{in}\, e^{-j\,\omega_i\, t} \qquad (4.25)$$

$$\overline{X}_{pk} = \frac{1}{T}\int_0^T \overline{x}(t)\, e^{-j\,k\,\omega t}\, dt \qquad k = 0, 1, 2, \ldots, \infty$$

$$\overline{X}^*_{nk} = \frac{1}{T}\int_0^T \overline{x}(t)\, e^{+j\,k\,\omega t}\, dt \qquad k = 1, 2, \ldots, \infty$$

$$\overline{x}(t) = \sum_{k=0}^{\infty} \overline{X}_{pk}\, e^{\,j\,k\,\omega t} + \sum_{k=1}^{\infty} \overline{X}^*_{nk}\, e^{-j\,k\,\omega t}$$

$$\bar{i}_i = \frac{2P_0}{3\bar{E}_{ip}^*} e^{j\omega_i t} - \frac{P_0}{3\left|\bar{E}_{ip}\right|^2} \underbrace{\sum_{k=-\infty}^{\infty}}_{k\neq 1} \Delta\bar{E}_{ik}\, e^{jk\,\omega_i\, t} -$$

$$- \frac{P_0}{3\bar{E}_{ip}^{*\,2}} \underbrace{\sum_{k=-\infty}^{\infty}}_{k\neq 1} \Delta\bar{E}_{ik}^*\, e^{j(2-k)\,\omega_i\, t}$$

$$\Delta i_{i_{RMS}} = \sqrt{\frac{2}{3}}\frac{P_0}{\left|\bar{E}_{ip}\right|}\sqrt{\frac{1}{4}\underbrace{\sum_{k=-\infty}^{\infty}}_{k\neq 1}\left|\frac{\Delta\bar{E}_{ik}}{\bar{E}_{ip}} + \frac{\Delta\bar{E}_{i(2-k)}^*}{\bar{E}_{ip}^*}\right|^2}$$

$\bar{e}_o$ $\bar{i}_o$

$$\bar{i}_i = \frac{2P_0}{3\bar{E}_{ip}^*}\left[1 + \frac{1}{2\bar{E}_{ip}}\Delta\bar{\psi}_1 - \frac{1}{2\bar{E}_{ip}^*}\Delta\bar{\psi}_1^*\right]e^{j\omega_i t} + + \frac{P_0}{3\bar{E}_{ip}^*}\underbrace{\sum_{k=-\infty}^{\infty}}_{k\neq 1}\left[\frac{1}{\bar{E}_{ip}}\left(\Delta\bar{\psi}_k - \Delta\bar{E}_{ik}\right) - \frac{1}{\bar{E}_{ip}^*}\left(\Delta\bar{\psi}_{2-k}^* + \Delta\bar{E}_{i2-k}^*\right)\right]e^{jk\omega_i t}$$

$$\Delta\bar{\psi} = \sum_{k=-\infty}^{\infty}\Delta\bar{\psi}_k\;\; e^{j\,k\,\omega_i\,t}$$

$$\bar{i}_i = \frac{2P_0}{3\bar{E}_{ip}^*} e^{j\omega_i t} - \frac{2P_0}{3\left|\bar{E}_{ip}\right|^2} \underbrace{\sum_{k=-\infty}^{\infty}}_{k\neq 1} \Delta\bar{E}_{ik}^*\, e^{jk\,\omega_i\, t}$$

$$GIDF = \sqrt{\frac{2}{3}}\frac{\Delta i_{i_{RMS}}}{\left|\bar{I}_{ip}\right|}$$

$$\Delta e_{i_{RMS}} = \sqrt{\frac{3}{2}}\sqrt{\underbrace{\sum_{k=-\infty}^{\infty}}_{k\neq 1}\left|\Delta\bar{E}_{ik}\right|^2}$$

$$\Delta i_{i_{RMS}} = \frac{2}{3}\frac{P_0}{\left|\bar{E}_{ip}\right|^2}\Delta e_{i_{RMS}}$$

$$\bar{i}_i = \frac{2P_0}{3\bar{E}_{ip}^*} e^{j\omega_i t} - \frac{2P_0}{3\bar{E}_{ip}^{*2}} \underbrace{\sum_{k=-\infty}^{\infty}}_{k\neq 1} \Delta\bar{E}_{ik}^*\, e^{j(2-k)\,\omega_i\, t}$$

$$\bar{i}_i = \frac{2P_0}{3\overline{E}_{ip}^*} e^{j\omega_i t} + \frac{2P_0}{3\overline{E}_{ip}^*} \sum_{k=1}^{\infty} \left(- \frac{\overline{E}_{ih}^*}{\overline{E}_{ip}^*} \right)^k e^{-j[k(h-1)-1]\omega_i t}$$

$$\frac{1}{\bar{e}_i^*} = \frac{1}{\left(\overline{E}_{ip}^* \, e^{-j\,\omega_i\,t} \; + \; \overline{E}_{ih}^* \, e^{-j\,h\,\omega_i\,t} \right)} = \sum_{\rho=-\infty}^{\infty} \overline{B}_\rho \, e^{j\,\rho\,\omega_i\,t}$$

$$\bar{e}_i \; = \; \overline{E}_{ip} \, e^{j\,\omega_i\,t} \; + \; \sum_{\mathrm{h}} \overline{E}_{ih} \, e^{j\,h\,\omega_i\,t}$$

with $h \; = \; 3\,m \; + \; 1, \;\; m \; = \pm 1, \pm 2, \ldots$

$$\bar{e}_i \; = \; \tfrac{2}{3} (e_a + e_b \; e^{j\frac{2}{3}\pi} + e_c \; e^{j\frac{4}{3}\pi})$$

$$\bar{v}_i = \frac{2}{3}\left(v_{ab} + \bar{a} v_{bc} + \bar{a}^2 v_{ca}\right) = v_i(t)\, e^{j\alpha_i(t)} \qquad (5)$$

where $\bar{a} = e^{j2\pi/3}$

The voltage vector $\bar{e}_i$ defined by the line-to-neutral voltages can be expressed as

$$\bar{e}_i = \frac{2}{3}\left(e_a + \bar{a} e_b + \bar{a}^2 e_c\right) = \frac{1}{\sqrt{3}} \bar{v}_i e^{-j\pi/6} \qquad (6)$$

$$p_i = \frac{3}{2} \bar{e}_i \bullet \bar{i}_i = \frac{3}{4}\left(\bar{e}_i\, \bar{i}_i^{\,*} + \bar{e}_i^{\,*}\, \bar{i}_i\right) = p_o \qquad (11)$$

(13)

$$\bar{e}_i = \bar{E}_{ip} e^{j\omega_i t} + \bar{E}_{in}^* e^{-j\omega_i t} = \bar{e}_{ip} + \bar{e}_{in}^* \qquad (14)$$

$$\bar{i}_i = \frac{2}{3} \frac{p_o}{\bar{E}_{ip}^*} e^{j\omega_i t} + \frac{2}{3} \frac{p_o}{\bar{E}_{ip}^*} \sum_{k=3,5..}^{\infty} \left(-\frac{\bar{E}_{in}}{\bar{E}_{ip}^*}\right)^{\frac{k-1}{2}} e^{jk\omega_i t} \qquad (15)$$

$$\bar{\Psi} = \bar{E}_{ip}\, e^{j\omega_i t} - \bar{E}_{in}^*\, e^{-j\omega_i t} = \bar{e}_{ip} - \bar{e}_{in}^*, \qquad (16)$$

$$\bar{i}_i = \frac{2}{3} \frac{p_o}{\left|\bar{E}_{ip}\right|^2 - \left|\bar{E}_{in}\right|^2} \left[\bar{E}_{ip} e^{j\omega_i t} - \bar{E}_{in}^* e^{-j\omega_i t}\right] \qquad (17)$$

$$HD_{11} = \frac{\sqrt{\sum_{k=2}^{11} I_{k\,max}}}{I_{1max}} \qquad (18)$$

$$I_{i_{RMS}} = \sqrt{\frac{1}{T}\int_0^T (\, i_a^2 + i_b^2 + i_c^2 \,)\, dt} \qquad (19)$$

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Matrix Converters

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