

POWER TRANSFER THROUGH MULTI-PURPOSE SWITCHING-MODE CONVERTERS

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Abstract- In this paper, the power transfer through a multi-purpose switching-mode converter is studied. Many authors presented the separate functions of the switching mode converters as active power filters, reactive power compensator and unity power factor rectifier. In this paper we present the simultaneity of those three functions and the capability of power transfer is discussed in detail. The results of this research are intended to be a guideline for application designers.

I. INTRODUCTION

The increasing use of power electronic devices has been issuing serious problems on harmonics and reactive power to an electric supply system in recent years. It has become more and more essential to reduce the harmonics to acceptable levels recommended by standards such as IEC 1000-3-2 or EN60555.

Due to the progress in power electronic devices and control, the pulse width modulation converters (PWM) working as shunt active power filters (APF) or as unity power factor rectifiers (UPFR) are the right solutions to reduce the harmonic level in the line current [1-4]. The separate functions of the switching mode converters were studied, such as APF in [5], UPFR in [6]-[8]. Other papers such [9] studied integrated active rectifier and power quality conditioning, but have not described the dual nature of the system in detail. The analysis of the simultaneous operation of all the mentioned functions has been initiated in [11]. This power transfer analyse through a multi-purpose switching-mode converter is continued in this paper.

II. SYSTEM CONFIGURATION

The proposed system is presented in figure 1. The central component of the system is a full bridge switching mode converter built with IGBT's. The system is dimensioned for operation at 3kW, primarily for experimental purposes. The connection with the ac supply network is realised via the filter inductance Z_F (L_f, R_f). The capacitor C represents the energy storage element. The switching-mode converter will act as power quality conditioner in the presence of a non-linear current with reactive component. The system acts as a unity power factor rectifier, supplying a dc

load irrespective of whether the non-linear load draws any current or not. As input parameters for the control system, a minimal solution was used: supply current, supply voltage, dc bus voltage and current.

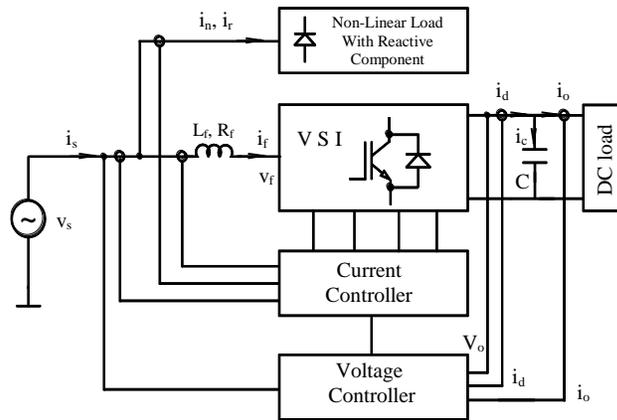


Fig.1 System configuration

This study is done on a single-phase model supplied from a 220V power supply, with dc bus voltage 500V, filter inductance of 7.2mH and capacitor of 1600 μ F.

III. POWER BALANCE PRINCIPLE

This analysis is intended to clarify the power exchange between the supply, non-linear load and the converter while it performs separate or simultaneous functions of reactive power compensation, harmonic compensation and unity power factor rectification. Throughout the analysis the AC bus will be considered to be infinite and no voltage distortion is taking place. Neglecting the losses of the H converter we can write the relation between the instantaneous power delivered by the supply (p_s) and the instantaneous power drawn by the non-linear load (p_n) and the active converter (p_c):

$$p_s = p_n + p_c \quad (1)$$

Where:

$$p_s = v_s(t) \cdot i_s(t) \quad (2)$$

$$v_s(t) = \hat{V}_s \sin(\omega t) \quad (3)$$

$$i_s(t) = \hat{I}_s \sin(\omega t) \quad (4)$$

$$p_n = v_s(t) \cdot i_n(t) \quad (5)$$

$$i_n(t) = \sum_{h=1,3,5,\dots}^{\infty} I_{nh} \sin(n\omega t - \varphi_n) \quad (6)$$

$$p_c = v_s(t) \cdot i_f(t) \quad (7)$$

After compensation the instantaneous power delivered by the supply is:

$$p_s = P_s(1 - \cos 2\omega t) = V_{sr} \cdot I_{sr}(1 - \cos 2\omega t) \quad (8)$$

Where P_s is the dc component of $p_s(t)$ and represents the active power delivered by the supply. The instantaneous power drawn by the non-linear load is:

$$p_n(t) = P_n + \tilde{p}_n(t) \quad (9)$$

Where P_n is the active power used by the non-linear load and $\tilde{p}_n(t)$ is the instantaneous fluctuant/distortion power due to the same non-linear load.

$$P_n = V_{sr} \cdot I_{nr} \cdot \cos \varphi_1 \quad (10)$$

The instantaneous power transferred through the active converter is:

$$p_c(t) = p_n(t) - P_s + P_o = P_n - P_s + \tilde{p}_n(t) = P_c + \tilde{p}_c(t) \quad (11)$$

$$\text{But: } P_c = P_n - P_s + P_o \quad (12)$$

$$\text{Therefore: } \tilde{p}_c(t) = \tilde{p}_n(t) \quad (13)$$

In steady state, the fluctuating power $\tilde{p}_c(t)$ at the output of active converter compensates the fluctuating power of the non-linear load. Equation (13) expresses the active power exchange between the supply, non-linear load and active converter. If we neglect the losses in the H converter, then the fluctuating power $\tilde{p}_c(t)$ is converted into the ripple voltage $\tilde{v}_o(t)$ across the condenser. When a transient change in the active power demanded by the load occurs, the storage element (C) should be capable to compensate this unbalance. This results in a variation of the dc bus voltage. If the active power delivered by the source was inferior to the load demand ($P_c > 0$), then the average (V_o) voltage across the capacitor decreases. If the load demands less active power ($P_s < 0$), then V_o increases. The variation of the dc bus is compensated by the voltage regulator [11].

The relation between the components of the current: active (i_a), reactive (i_r) and non-linear (i_n - harmonic content) was another aspect studied in this paper. Generally, the current can be written:

$$i(t) = i_a(t) + i_r(t) + i_n(t) \quad (14)$$

$$i_a(t) = I_1 \sin(\omega t - \varphi_1) \quad (15)$$

$$i_r(t) = I_1 \cos(\omega t - \varphi_1) \quad (16)$$

$$i_n(t) = \sum_{j=3,5,7,\dots}^{\infty} I_{hj} \sin(h\omega t - \varphi_j) \quad (17)$$

For each of these currents we can associate a phasor. Two phasors are orthogonal if the scalar product is nil [10]. Using the definition of the scalar product and equations (15) to (17), it is possible to find that:

$$\overline{i_a \cdot i_r} = 0 \quad (18)$$

$$\overline{i_a \cdot i_h} = 0 \quad (19)$$

$$\overline{i_r \cdot i_h} = 0 \quad (20)$$

If three phasors are orthogonal one on each other, then they can be represented as the sides of a rectangular parallelepiped.

For the current components in phase with the voltage but also for the orthogonal components, the superposition principle is applicable. By means of simulation and experiments the orthogonal relation among the three components of the current will be shown. The rms value of the current will be used: I_{sr} - rms supply current, I_{rr} - rms reactive current, I_{nr} - rms non-linear current, I_{dr} - rms output converter current, I_{fr} - rms input converter/filter current and I_{or} - rms output current.

The analysis was done first by means of simulations using Matlab 6.

IV. SINGLE FUNCTION ANALYSIS

4.1. Reactive Power Compensation

To illustrate the case of pure reactive power compensation, the dc load is not connected ($P_o = 0$) and the non-linear load has no harmonics but has a phase-shift relative to the supply voltage. The figure 2 presents the graphs of p_s , p_r (the instantaneous power required by the reactive load with a phase-shift of approximately -31°) and p_c .

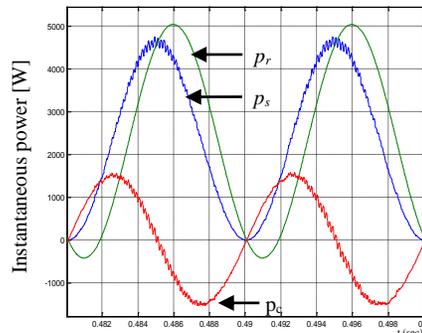


Fig. 2 Reactive Power Compensation

Analysing the graphs from figure 2 shows that $p_s = p_r + p_c$. The negative part of p_c implies that the converter is

injecting the difference between p_r and p_s . The positive p_c means the converter is drawing power to compensate $p_s - p_r$; this power is being used to keep the storage element charged constantly. This means that the rms reactive component of the load current (i_r) comes from the storage element C (i_d) via the converter:

$$I_{dr} = I_r \sin \varphi \quad (21)$$

And now, the current i_s provides only the active component of i_r . But, according to equations (18) the active and reactive components of any current are orthogonal and:

$$I_{nr}^2 = I_{sr}^2 + I_{dr}^2 \quad (22)$$

Using the rms values $I_{nr} = 12.4$ A, $I_{sr} = 10.5$ A, $I_{fr} = 6.8$ A and $I_{dr} = 6.8$ A determined from the above simulation, the equation (22) is verified with a good approximation.

4.2. Harmonic Compensation

To illustrate the case of pure harmonic distortion consider that the non-linear load does not have any reactive component and the DC load is not connected ($P_o = 0$). Non-fundamental harmonic current exists in the non-linear load as well as fundamental current with a unity displacement power factor. Assume that non-linear load has a 72% harmonic content and the phase shift of the fundamental is close to zero. In the case of harmonic compensation, the graphs from figure 3 prove again $p_s = p_n + p_c$ for all points in time. In this case the current passing the converter is the harmonic content of i_n or:

$$I_{dr} = I_{hr} = I_{nr} \sqrt{\frac{THD^2}{1+THD^2}} \quad (23)$$

The fundamental component of i_n comes from supply source, and according to equation (19) results:

$$I_{nr}^2 = I_{sr}^2 + I_{dr}^2 \quad (24)$$

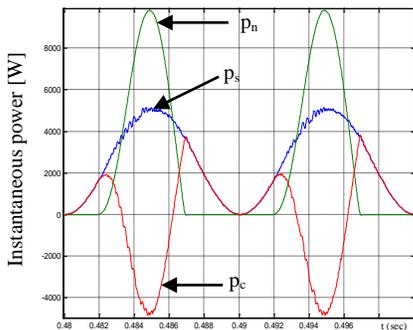


Fig.3 Harmonic compensation

Analysing the rms values of $I_{nr} = 14.5$ A, $I_{sr} = 11.7$ A, $I_{fr} = 8.8$ A and $I_{dr} = 8.8$ A, it can be seen that equations (23) and (24) are valid. There is however greater error due to the ripple and the small phase shift of the fundamental of the non-linear current.

4.3. Unity Power Factor Rectifier

To illustrate the case of a unity power factor rectifier the non-linear current is zero and there is a DC load of 6A. From the figure 4 it can be seen that the power drawn by the converter is purely sinusoidal as for a purely resistive load (unity power factor) and $\hat{p}_s = 2P_o$.

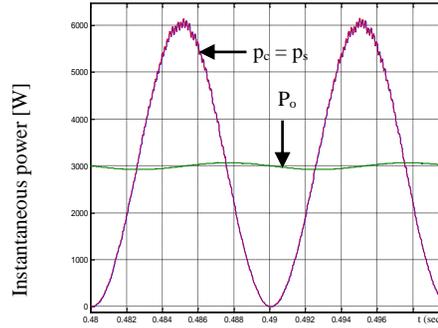


Fig.4 Unity Power Factor Rectifier

Assuming a non-losses converter, in the case of unity power factor, the current that passes it from the supply is needed only to produce dc power:

$$I_{sr} = I_{fr} = I_{dr} \quad (25)$$

In this case $P_s = P_o$ and:

$$I_{dr} = I_{or} \frac{V_o}{V_{sr}} \quad (26)$$

Measuring the rms values $I_{sr} = 13.7$ A, $I_{fr} = 13.7$ A, $I_{dr} = 13.7$ A and $I_{or} = 6$ A results, the equations (25) and (26) are verified with a very good approximation.

V. SIMULTANEOUS POWER CONDITIONING

5.1. Stationary 3 kW dc output power and reactive load with phase-shift of -31° .

The graphs from the figure 5 prove again that: $p_s = p_r + p_c$. In this situation, the converter compensates the reactive component of the non-linear current and provides dc power for the load. The supply will provide the active component of the non-linear current and another component for dc load, both in phase with the voltage and:

$$I_{sr} = I_{rr} \cos \varphi + I_{or} \frac{V_o}{V_{sr}} \quad (27)$$

But the currents that pass the converter are orthogonal and:

$$I_{dr}^2 = I_{rr}^2 \sin^2 \varphi + \left(I_{or} \frac{V_o}{V_{sr}} \right)^2 \quad (28)$$

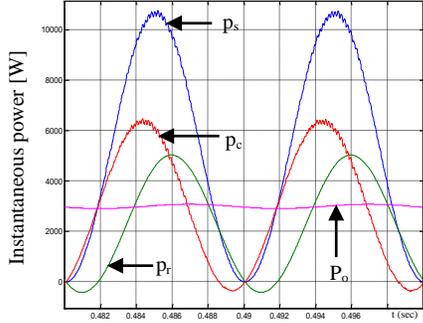


Fig. 5 Power Flow for Reactive Compensation and Unity Power Factor Rectifying

Analysing the rms values $I_{sr} = 24.2$ A, $I_{rr} = 12.41$ A, $I_{fr} = 15.3$ A, $I_{dr} = 15.3$ A and $I_{or} = 6$ A, results that the equations (27) and (28) are valid within a good approximation.

5.2. Stationary non-linear current with 72% harmonic content and 3 kW dc output power

This situation is represented by the graphs from figure 6 for this situation, and again $p_s = p_n + p_c$. In this situation the supply provides the power for the dc load and the fundamental of the non-linear current and:

$$I_{sr} = \frac{I_{nr}}{\sqrt{1+THD^2}} + I_{or} \frac{V_o}{V_{sr}} \quad (29)$$

Through the converter passes now two orthogonal currents the harmonic compensation current and the active component necessary for the dc load:

$$I_{dr}^2 = I_{nr}^2 \frac{THD^2}{1+THD^2} + \left(I_{or} \frac{V_o}{V_{sr}} \right)^2 \quad (30)$$

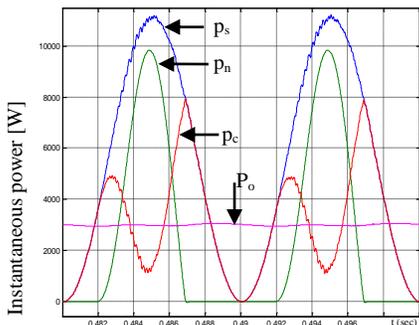


Fig. 6 Power Flow for Harmonic Compensation and Unity Power Factor Rectifying

Analysing the rms values $I_{sr} = 25.4$ A, $I_{nr} = 14.5$ A, $I_{fr} = 16.26$ A, $I_{dr} = 16.3$ A and $I_{or} = 6$ A results that (29) and (30) are verified within a good approximation.

5.3. Active power filter

The graphs from the figure 7 prove again that: $p_s = p_r + p_n + p_c$. In this situation, the converter compensates the reactive and harmonic components of the non-linear current. The supply will provide the active component of the non-linear current and:

$$I_{sr} = I_{rr} \cos \varphi + \frac{I_{nr}}{\sqrt{1+THD^2}} \quad (31)$$

But the currents that pass the converter are orthogonal and:

$$I_{dr}^2 = I_{rr}^2 \sin^2 \varphi + I_{nr}^2 \frac{THD^2}{1+THD^2} \quad (32)$$

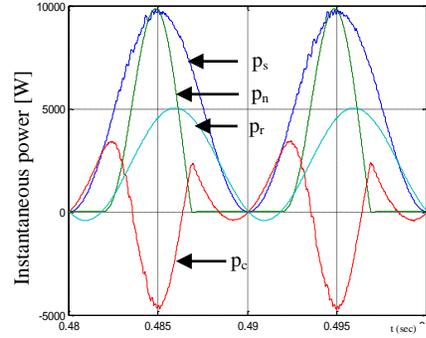


Fig. 7 Power Flow for APF

Analysing the rms values $I_{sr} = 22.3$ A, $I_{rr} = 12.4$ A, $I_{nr} = 14.5$ A, $I_{fr} = 10.4$ A and $I_{dr} = 10.4$ A, results that (31) and (32) are valid within a good approximation.

5.4. Integrated compensator

The complete situation with all three functions implemented is presented by the graph from figure 8. For this general situation and after the compensation, the currents in phase with the supply voltage drawn from the supply are the active component of the non-linear current (i_n and i_r) and the component necessary for dc load:

$$I_{sr} = \frac{I_{nr}}{\sqrt{1+THD^2}} + I_{rr} \cos \varphi + I_o \frac{V_o}{V_{sr}} \quad (33)$$

But the converter insures the compensating component for harmonic content of the non-linear current (i_n), reactive current of i_r and active current for dc load. These components are orthogonal (18), (19), (20) and:

$$I_{dr}^2 = I_{nr}^2 \frac{THD^2}{1+THD^2} + I_{rr}^2 \sin^2 \varphi + \left(I_{or} \frac{V_o}{V_{sr}} \right)^2 \quad (34)$$

VII. CONCLUSIONS

The simulation graphs from figures 2 to 8 and the experimental results prove that instantaneous power handled by a multi-purpose switching-mode converter, performing simultaneous functions of reactive compensator, harmonic compensation and unity power factor rectifier, is described by $p_s = p_n + p_r + p_c$. Each of these functions of the converter can be seen to be orthogonal (18), (19), (20), and each of the functions can be designed and implemented by using superposition techniques.

The rms current through the converter I_{dr} can be expressed with a good approximation by (34).

The total harmonic distortion of the supply current was not affected by the small distortion (3%) of the supply voltage. The shape of reference current, switching frequency and the value of input filter are the main parameters that influence the supply current harmonic content.

The equation (34) could be used as a design guide for application of multi-functionality switching-mode converters.

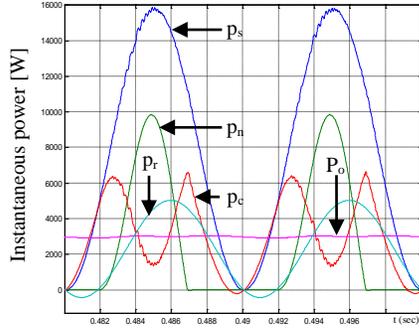


Fig. 8 Power Flow for Integral Compensation

The rms values of the main parameters are: $I_{sr} = 35.9$ A, $I_{nr} = 14.5$ A, $I_{rr} = 12.4$ A, $I_{dr} = 17.1$ A and $I_{or} = 6$ A and these values check (33) and (34) within a good approximation.

VI. EXPERIMENTAL RESULTS

The parameters of the experimental platform: $V_s = 220$ V, dc bus voltage $V_o = 500$ V, storage element $C = 1600$ μ F, input filter inductance 7.2 mH with 16.8 m Ω and the power devices used were Semikron SKM 100GB123D-IGBTs. The non-linear load consists from diode bridge rectifier and the reactive current is created by means of RL components.

The experiments were done in similar conditions with the simulations and the results are summarised in the table 1: case 1 - reactive compensation, case 2 - harmonic compensation, case 3 - unity power factor rectifying, case 4 - reactive power compensation and unity power factor rectifying, case 5 - harmonic compensation and unity power factor rectifying, case 6 - APF and case 7 - integral compensation.

TABLE 1

Case	I_{sr} (A)	I_{rr} (A)	I_{nr} (A)	I_{dr} (A)	I_r (A)	I_{or} (A)
1	10.8	12.52	0	6.78	6.78	0
2	11.64	0	14.3	8.71	8.71	0
3	12.8	0	0	12.8	12.8	5.55
4	23.5	12.52	0	14.42	14.42	5.55
5	24.3	0	14.3	15.45	15.45	5.55
6	22.3	12.52	14.3	10.21	10.21	0
7	35	12.52	14.3	16.35	16.35	5.55

From the above data results that super positioning (33) is checked within an error less than 2% and orthogonality (34) within 4%. The losses in the converter contributed to this increase in error.

The total harmonic distortion of the supply current for the above cases is presented in table 2.

TABLE 2

Case	1	2	3	4	5	6	7
THD (%)	2.8	3.4	2.8	2.6	2.6	2.9	2.7

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