Active Ac Line Conditioner for a Cogeneration System

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Abstract - This paper deals with a cogeneration system which can produce electric energy from low pressure saturated steam or natural gas. The system consists of a high speed turbine coupled to a synchronous generator, which is connected to the ac line by a power conditioning system. In this paper a novel control strategy is proposed in order to provide not only the active power obtained from the mechanical side, but reactive power as well. In this way, the power conditioning system can also be efficiently used as active filter. This new feature reduces the pay back time without increasing the investment cost. The theoretical analysis of the control system is confirmed by computer simulations.

I. Introduction

Industrial plants often provide different types of energy which can be partially converted into electric energy by means of a cogeneration system, with the aim to improve the overall efficiency of the plant. If low pressure steam is available, an efficient utilisation of the related energy is achieved employing a high speed turbine. In order to avoid the need of a reduction gear, the use of high speed synchronous generators directly coupled to the turbine shaft is considered a valid solution. The electric energy produced by the generator can be fed into the mains by an ac/ac Power Conditioning System (PCS) [1]-[3]. Using a suitable control technique, the PCS can operate as active ac line conditioner. In this way, additional tasks, such as compensation of reactive power and current harmonics of non-linear loads, can be performed. These features can be achieved being the topology of the dc/ac conversion unit like that of a shunt active power filter [4]-[7].

A new control strategy for the ac line power conditioner, which can be implemented on a DSP based controller, is investigated. The control method performs the direct regulation of the source currents, which are forced to be sinusoidal and in phase with the corresponding line-to-neutral voltages [8-11]. The behaviour of the power conditioning system has been verified in steady-state and transient operating conditions. The analysis has been carried out by numerical simulations using PSpice tools.

II. Electromechanical System

The simplified block diagram of the whole system is shown in Fig.1. The system is based on two independent control loops. The former is a pressure control loop, which keeps the outlet steam pressure at a settled reference value. The latter operates on the electric side of the cogeneration system. A relevant task of this controller is to maintain the speed of the rotating group close to its rated value, regardless of the turbine torque. Being the dc-link voltage proportional to the generator speed, this task is indirectly achieved keeping the dc-link voltage of the ac/ac converter close to its

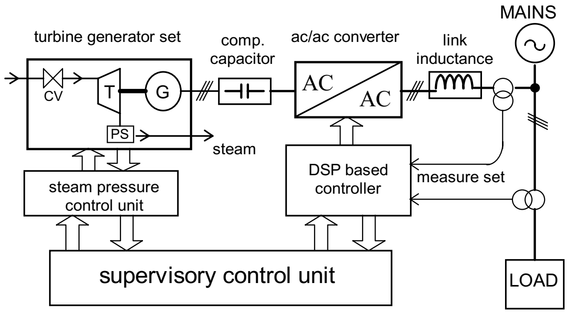

Fig. 1: Block diagram of the cogeneration system

reference value.

The operating conditions of the working medium and the ac network requirements determine the choice of the electromechanical and electronic parts of this cogeneration system. The pressure and temperature values of the steam suggest the use of a special high speed turbine, characterized by high efficiency and small size.

The control unit acts on the inlet valve actuator CV in order to regulate the outlet steam pressure, which is monitored by the pressure sensor PS.

The turbine T is directly coupled to the synchronous generator G which supplies the three-phase ac/ac converter.

The rated speed of the turbine is 12000 rpm. Using a 4-pole synchronous machine, a three-phase system of voltages at a frequency of 400 Hz is generated. As a result of using rare-earth magnets for the generator excitation, the effects of the armature reaction are reduced. Then, the synchronous inductance is lower than that of traditional machines. However, due to the high stator frequency, the synchronous reactance is still high, causing a large voltage drop at the rated current. This in turn determines a reduction of the power that can be fed to the mains. In order to overcome this drawback, the synchronous reactance can be compensated by introducing series capacitors, as it will be discussed in Section III.

In this work the turbine-generator set is represented by a simplified model. A transfer function, which takes the mechanical losses and the inertia of the two machines into account, gives a relationship between the electrical power available at the generator terminals and the mechanical speed.

III. AC/AC Conversion Scheme

The electric energy produced by the turbine-generator set can be fed into the mains by the ac/ac power converter shown in Fig. 2.

The ac/ac converter is realised by a three-phase diode rectifier supplying the dc-link, and a Voltage Source Inverter (VSI) connected to the mains. The parallel connection to the mains is realised through three ac-link inductances.

The main feature of the PCS is to deliver the rated active power to the mains. The second feature is the possibility for the PCS to operate as active filter, i.e. compensation of reactive power and current harmonics due to reactive or non-linear loads connected to the mains.

For a given value of the mechanical speed, the dc-link voltage V_{dc} decreases as the dc-link current I_{dc} increases. This is due to the effects of the synchronous reactance and introduces unacceptable limitations for the power fed to the mains. The compensation of the voltage drop across the synchronous reactance X_S can be obtained by means of series connected capacitors. The value of their capacitance C_S is selected in order to determine a series resonance with the synchronous inductance at the rated frequency of 400 Hz.

Fig. 3 shows the dc-link voltage as a function of the dc-link current for different turbine speeds, namely different stator frequencies. At the rated speed the compensation effect is satisfactory in a wide interval around the rated current (I_{dc}=30 A). As Fig. 3 shows, the dc-link voltage behavior deteriorates even considering small changes (± 5%) of the frequency.

With reference to the scheme of Fig. 2, the power available at the dc-link is given by $P_{dc} = V_{dc}\, I_{dc}$. Keeping the dc-link voltage V_{dc} close to its reference value V_{dc}^{*} it is possible to deliver the rated active power to the mains.

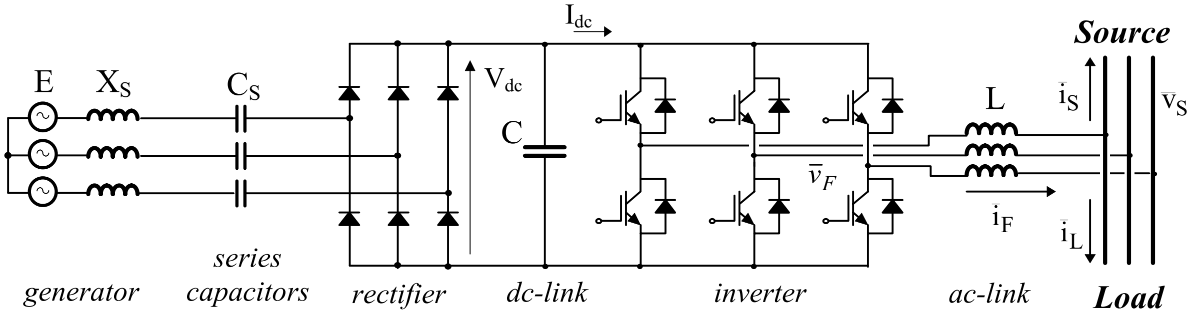

Fig. 2: Scheme of the ac/ac conversion system

The rectifier output is connected to the inverter through the dc-link (Fig. 2). A shunt capacitor C is applied to the dc-link in order to smooth the rectifier output voltage and to allow the operation as active power filter.

The voltage source inverter employs Insulated Gate Bipolar Transistor (IGBT) as controlled switches. The ac-link inductors have a large influence on the performance of the PCS. For a given value of the inverter output voltage, the reactance value (X=ωL) determines the maximum reactive power the active filter is able to compensate. Furthermore, it can be noted that the inductance L affects the dynamic performance of the current regulator loop, yielding a limit for the maximum harmonic order the filter is able to compensate.

The load and filter currents, together with the dc-link voltage and the source voltages, are measured and used in the control system to generate the PWM signals for the inverter.

IV. Reactive Power Compensation

In addition to the rated active power, the PCS must supply some amount of reactive power. This capability is defined by the maximum current value on the ac side of the inverter. If a given quantity of reactive power Q_F is required in addition to the rated active power P_{FR}, an over rating of the converter current is needed.

Under three-phase balanced operating conditions, the analysis can be developed using the per-phase equivalent circuit. Fig. 4 shows the phasor diagram of the inverter-mains coupling equations, at the fundamental frequency. In particular, $\overline{V}_F$ and $\overline{V}_S$ are the filter and the source line-to-neutral voltages, i.e., the voltages at the two sides of the ac-link reactance. The resistance of the ac line inductor is neglected.

The current $\overline{I}_{FA}$ is the active component of the filter current, and it represents also the rated filter current, corresponding to the rated active power P_{FR} delivered to the mains with unity power factor.

By increasing the filter current to the value $\overline{I}_F$, a certain amount of reactive power Q_F can be supplied by the filter, in addition to the rated active power. From the phasor diagram of Fig. 4 the following relationship can be derived

$$\frac{Q_F}{P_{FR}} = \sqrt{\left(\frac{I_F}{I_{FA}}\right)^2 - 1}\,. \tag{1}$$

A graphical representation of (1) is given in Fig. 5. This figure shows that in order to supply a reactive power equal to the active power (tan φ = 1), the filter current should be increased to 1.4 times its rated value.

However a current over rating of about 40% increases the converter cost of a small percentage (less than 10%). Furthermore, saving the reactive energy cost contributes to reduce the pay back time of the total investment cost.

According to the phasor diagram of Fig.4, the reactive power Q_F is given by

$$Q_F = V_S I_F \sin\varphi_F\,. \tag{2}$$

The rated active power can be expressed as

$$P_{FR} = \frac{V_S V_F}{X}\sin\delta\,. \tag{3}$$

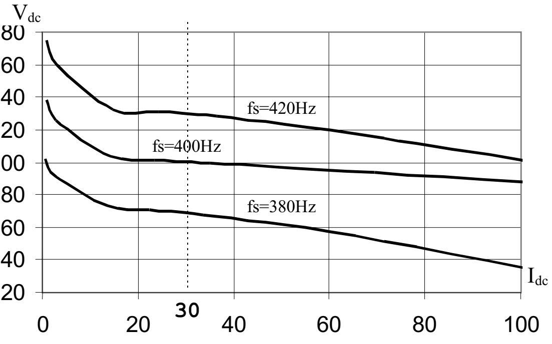

Fig. 3: Compensating effect of the capacitance C_S for different generator frequencies

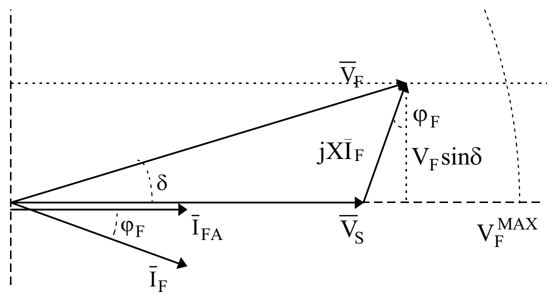

Fig. 4: Phasor diagram of the converter-mains coupling through the ac line reactance

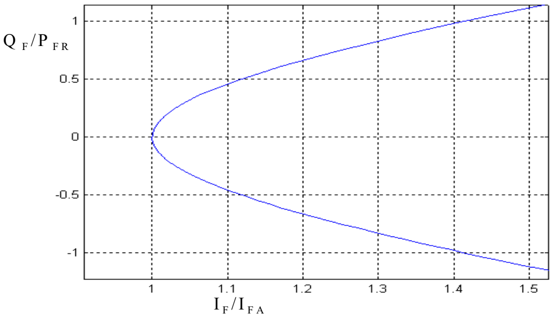

Fig. 5: Reactive power to rated active power ratio vs. converter current over rating

From the diagram of Fig. 4 it is also verified that

$$I_F \sin\varphi_F = \frac{V_F \cos\delta - V_S}{X}. \tag{4}$$

Substituting (3) and (4) into (2) yields

$$Q_F = \frac{\sqrt{V_F^2 V_S^2 - P_{FR}^2 X^2} - V_S^2}{X}. \tag{5}$$

For given values of V_S, V_F, and P_{FR}, the value of Q_F the PCS can supply to the mains is determined by the value of X. Higher is the value of X, lower will be the value of Q_F.

The maximum output voltage V_F^{MAX} of the inverter is limited by the value of the dc-link voltage. As a consequence, for a given value of the reactance X, (5) determines the maximum reactive power Q_F^{MAX} the PCS can supply together with the rated active power.

Fig. 6 shows the ratio of the reactive power to the rated active power as a function of the converter output voltage V_F, for different values of the ac line reactance X. As an example, assuming $V_S = 230V$ and $V_F = 300V$, in order to supply a reactive power $Q_F = P_{FR}$ the reactance X must be lower than 1.5 Ω.

V. Power Conditioning System

The aim of the PCS is to supply the rated active power P_{FR}, and to compensate reactive power and current harmonic components of non-linear loads connected to the mains. These requirements are obtained by tracking suitable reference values for the source currents. These reference values are generated by the dc-link voltage regulator, as it will be described in Section V-A. The ac current regulator must be able to keep the source currents close to their reference values by means of a suitable modulation technique applied to the Voltage Source Inverter (VSI), as it will be discussed in Section V-B.

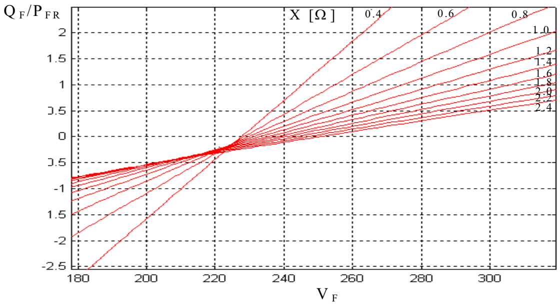

Fig. 6: Reactive power to rated active power ratio vs. converter output voltage, for different values of the reactance

For the analytical developments, the three-phase quantities are represented by space vectors, according to a stationary d-q transformation.

A. DC-Link Voltage Controller

The control strategy proposed for regulating the dc-link voltage is based on the principle summarised by the scheme shown in Fig. 7.

The reference current vector $\bar{i}_S^*$ is obtained by multiplying the unity vector $\hat{v}_S$, which is in phase with $\bar{v}_S$, by the reference source current magnitude I_S^*, given by the regulator R(s). This regulator can be a standard PI regulator. It operates on the instantaneous error between the reference value V_{dc}^* and the actual value V_{dc} of the dc-link voltage.

The aim of this control strategy is to obtain source currents almost sinusoidal and in phase with the corresponding line-to-neutral voltages. In this way, the source exchanges only active power with the conditioned load. The reactive and harmonic currents of the load act as perturbation terms.

When the load is not connected to the mains, the cogeneration system will supply the rated active power. As the load is switched on, the source will supply the difference between the active power required by the load and the active power delivered by the cogeneration system. In general, the reactive power of the load is compensated by the PCS. If the reactive power exceeds the converter ratings, the difference will be supplied by the source.

B. AC Current Controller

Once the reference source current $\bar{i}_S^*$ has been generated by the dc-link voltage controller, the ac current regulator must operate in order to keep the source current $\bar{i}_S$ close to its reference value. As a first step, the reference filter current $\bar{i}_F^*$ must be determined since the VSI acts directly on the filter current $\bar{i}_F$. This can be done by the following equation

$$\bar{i}_F^* = \bar{i}_S^* + \bar{i}_L \,, \tag{6}$$

where the load current $\bar{i}_L$ is a measured quantity. The reference voltage for the PWM-VSI can be determined on the basis of the filter current error $\Delta\bar{i}_F = \bar{i}_F^* - \bar{i}_F$, where $\bar{i}_F$ is a measured quantity. Neglecting the resistance of the ac line inductor, $\bar{v}_F^*$ can be calculated by the following voltage equation

$$\bar{v}_F^* = \bar{v}_S + L\frac{\Delta\bar{i}_F}{\Delta t} = \bar{v}_S + K\,\Delta\bar{i}_F \,, \tag{7}$$

where K is the gain of a proportional regulator. On the basis of (7), the block diagram shown in Fig. 8 can be derived. It can be noted that the filter current is regulated through a closed loop control scheme.

Assuming that the VSI can generate the reference voltage at each cycle period, i.e. $\bar{v}_F = \bar{v}_F^*$, the following transfer function for the filter current can be obtained

$$\bar{i}_F = \frac{1}{1+\frac{L}{K}s}\,\bar{i}_F^* \,. \tag{8}$$

Eq. 8 shows that the response of the ac current controller is represented by a first order low-pass filter with a time constant $\tau = L/K$. The PCS behaviour as active filter is mainly determined by the dynamic response of this current regulator.

Lower is L, faster is the current controller, and wider is the filter bandwidth. On the other hand, a high value of L reduces the HF harmonics of the currents injected into the mains by the PCS, improving the voltage quality at the point of common coupling. According to (8), a large value of L can be compensated by increasing the proportional gain K. However, this possibility is limited by the maximum output voltage of the VSI, which is determined by the fixed value of the dc-link voltage V_{dc}^*.

VI. Numerical Results

The electrical system represented in Fig. 2 has been numerically simulated by PSpice.

The generator is a 4-pole, permanent magnet, synchronous machine with the following parameters: $R_S = 114\ \text{m}\Omega$, $L_S = 37$ mH.

Using a series capacitance $C_S = 47.2\ \mu\text{F}$, the resonance with the synchronous inductance of the generator is obtained at the rated frequency of 400 Hz.

The reference dc-link voltage is $V_{dc} = 700$ V. The capacitor of the dc-link has a capacitance of 4200 μF. The switches of the IGBT inverter are controlled by a PWM technique based on a carrier frequency $f_C = 10$ KHz. The three-phase ac line inductor parameters are L = 2.5 mH, R = 0.1 Ω. Ideal sinusoidal source voltages (380 V, 50 Hz) have been assumed.

The performance of the cogeneration system has been evaluated in steady-state and transient operating conditions with reference to two types of load.

The former is a three-phase linear load (27 A, cosφ = 0.866), and the results obtained are represented in Figs. 9 and 10. The latter is a non-linear load consisting of a full bridge rectifier supplying a R-L load (R=20 Ω, L=60 mH).

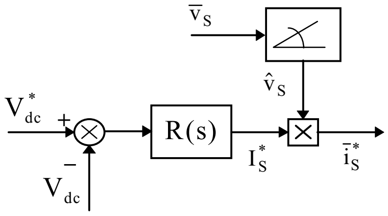

Fig.7: DC-link voltage controller

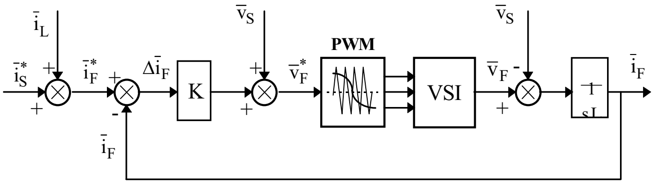

Fig. 8: AC current controller

Numerical results in steady-state and transient conditions

a) - filter current **b)** - source current **c)** - load current **d)** - dc-link voltage **e)** - source voltage

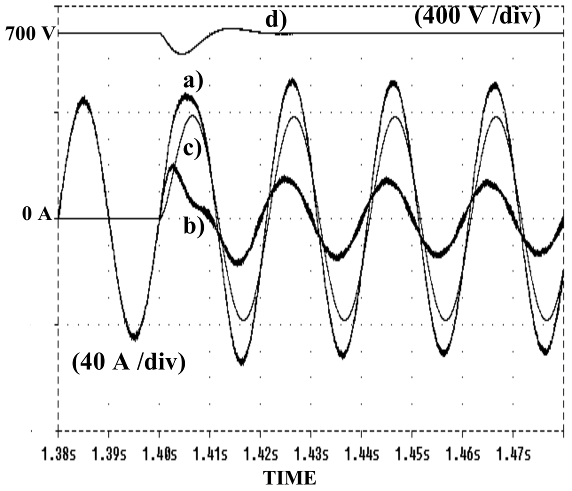

Fig. 9: Cogeneration system behavior in transient operating conditions. Load: R=7 Ω, L=13 mH

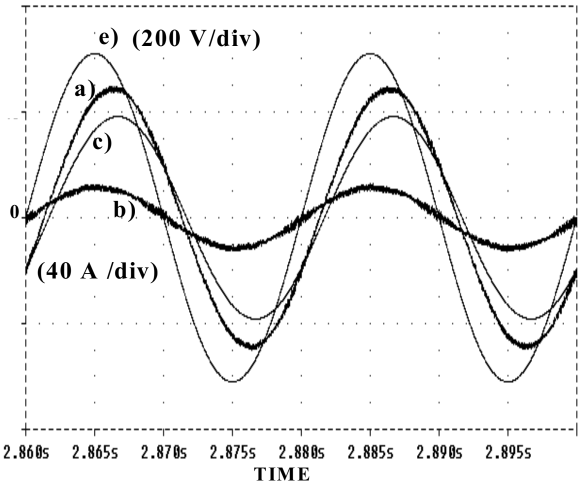

Fig. 10: Cogeneration system behavior in steady-state operating conditions. Load: R=7 Ω, L=13 mH

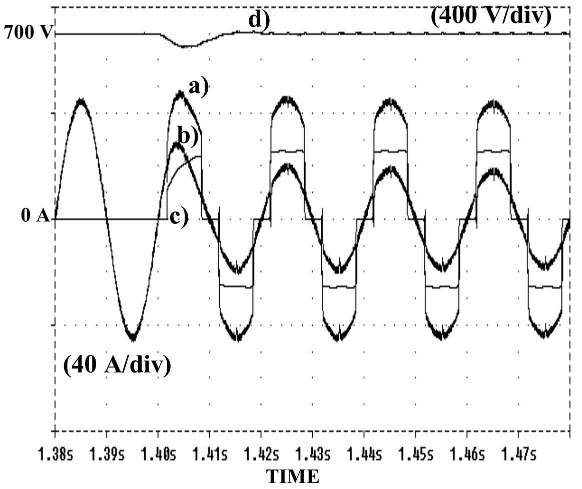

Fig. 11: Cogeneration system behaviour in transient operating conditions. Load: diode rectifier

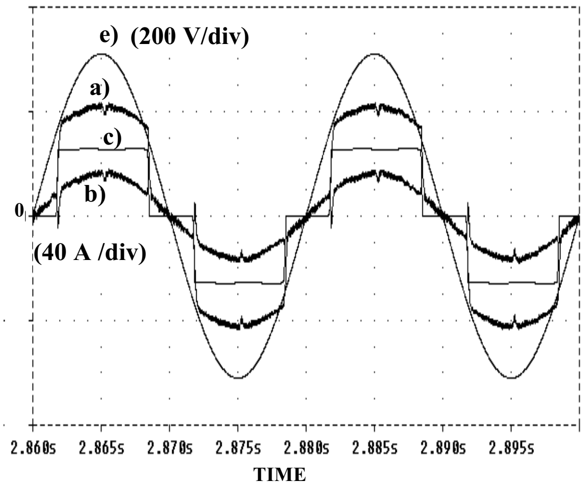

Fig. 12: Cogeneration system behaviour in steady-state operating conditions. Load: diode rectifier

The results obtained are represented in Figs. 11 and 12. The numerical results for both the linear and non-linear loads have been obtained using the same control parameters. In particular, the transfer function of the dc-link voltage regulator shown in Fig. 7 is $R(s) = P + I/s$, with $P = 2$, and $I = 700$.

With reference to Fig. 9, during the first 20 ms the load is switched off and the cogeneration system supplies only the rated active power to the mains. Then, the filter current (waveform a) is equal to the source current (waveform b). As the load is switched on, after a short transient of about 10 ms, a new steady-state operating condition is reached. The results obtained show that the control algorithm is fast enough to respond to large load changes. The cogeneration system supplies the same active power as before, and compensates the load reactive power. As it can be seen in Fig. 10, the source current (waveform b) is exactly in phase with the corresponding line-to-neutral voltage (waveform e), yielding a complete compensation of the load reactive power.

Fig. 11 shows the results obtained during the switching on of the non-linear load. In this case also, after a short transient a new steady-state operating condition is reached. The power conditioning system is able to compensate the low order harmonics of the load current. This is clearly illustrated in Fig. 12, where the source current is in phase with the corresponding line-to-neutral voltage, and shows an almost sinusoidal waveform.

VII. Conclusions

A power conversion system for a cogeneration plant has been analysed in this paper. It has been shown that using a suitable control technique the system can also operate as active filter. The control technique is based on two independent control loops. The former controls the dc-link voltage defining the reference value of the source current. The latter uses a PWM-VSI to force the filter current to track its reference value.

The ability of the system to behave as active filter has been verified by numerical simulations in steady-state and transient operating conditions, using either linear or non-linear loads. The results obtained show that, with an appropriate design of the two controllers, it is possible to compensate the reactive power of linear loads, as well as the low order current harmonics of non-linear loads.

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