Improved Fault Tolerance of Active Power Filter System

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Abstract: This paper investigates the utilization of a relatively simple topology that provides fault-tolerant operation for a three-phase system containing a shunt active power filter. With such a topology, when one of the filter converter legs is lost, the filter can still operate by connecting the grid neutral to a fourth converter leg. The structure proposed and the operating principles of the system are presented. The system model under fault condition is derived and a suitable control strategy is proposed. Experimental results are presented to demonstrate the correctness of the proposed solution.

I. INTRODUCTION

The strict regulations about the flow of electrical energy has stimulated the use active power compensation schemes [1, 2]. The active power compensation is normally achieved with the help of switching converters connected as an active filter to the load.

AC power systems are very sensitive to different types of failure occurring at the power converter. Whenever possible, the isolation of the fault is preferable to the stop of the system since it keeps the drive partially operative. In recent years different papers focused schemes of fault-tolerant converter systems [3-6].

This paper proposes the utilization of a fourth converter leg connected to the grid neutral for maintaining the system under power balanced operation whenever one of the filter converter legs in the drive system of Figs. 1(a) is lost. With the control strategy proposed, when one of the filter converter legs is lost, the power compensation can still be provided with only two phases, until it can be stopped with security. The control strategy permits to maintain the active power compensation except for the homopolar term that cannot be compensated.

II. SYSTEM DESCRIPTION

Figs. 1(a) present a shunt system composed by the grid source, a three-phase load and a voltage source converter. The grid source is composed by three balanced voltage sources ($e_{l1}$, $e_{l2}$, $e_{l3}$) with equal series resistances ($R_s$) and inductances ($L_s$). The switching converter of the active power filter is a voltage source converter ($VSC$) with equal series resistances ($R_f$) and inductances ($L_f$). This converter also has a fourth leg connected to the grid neutral. During a balanced operation the fourth leg is inactive.

The current at the output of the $VSC$ is controlled to deliver the reactive and harmonic current demanded by the load providing the active power filtering feature. The $dc$ side of the $VSC$ requires a capacitor bank with minimum energy storage capacity. The converter needs active power because the load voltage is different from the grid voltage (due to $R_s$ and $L_s$) and because the losses associated to its operation. The $VSC$ average power can be directly supplied from the grid. In this case, the active power filter control can be achieved by controlling the grid current in phase with the grid voltage, with amplitude is defined by $dc$-bus voltage regulation.

Figure 1(b) presents one possible system configuration after losing one of the active power filter legs (the phase 1 open). The fault detection is accomplished by using the methods presented in [7]. The relevant characteristics exhibited by the system can be preserved after the fault. However, after the fault, the filter cannot control all three-phase currents but, instead, it can control the $dq$ grid component current to be in phase with the corresponding $dq$ grid component voltage. This is done at the expenses of a homopolar current flowing in the grid.

III. BEFORE-FAULT MODEL

A. Three-phase model

The operation of the system given in Fig. 1(a) before the occurrence of the fault can be analyzed with the help of the equivalent circuits in Fig. 2(a). In this analysis the three phase load is represented by three current sources ($i_{l1}$, $i_{l2}$ and $i_{l3}$).

Kirchhoff’s laws applied to the equivalent circuit of Fig. 2(a) leads, for a generic phase $j$ ($j = 1, 2, 3$), to

$$e_{l_j} - v_{f, 0} - \delta_{0n} + u_j = R_s i_{l_j} + L_s \frac{di_{l_j}}{dt}$$

$$u_j = R_f i_{l_j} + L_f \frac{di_{l_j}}{dt}$$

where $\delta_{0n}$ is voltage difference between the neutral point

\[ A \]
of the filter converter (0) and neutral point of the grid (n) and \( R_t = R_s + R_f \) and \( L_d = L_s + L_f \).

Eliminating \( \delta_{0n} \) and using \( i_{s1} + i_{s2} + i_{s3} = i_1 + i_2 + i_3 = 0 \), a two-phase model can be obtained:

\[
\begin{bmatrix}
    e_{s1} \\
    e_{s3}
\end{bmatrix} =
\begin{bmatrix}
    v_{f12} \\
    v_{f31}
\end{bmatrix} +
\begin{bmatrix}
    u_{12} \\
    u_{31}
\end{bmatrix} =
\begin{bmatrix}
    R_t & -R_t \\
    -2R_t & -R_t
\end{bmatrix}
\begin{bmatrix}
    i_1 \\
    i_2
\end{bmatrix} +
\begin{bmatrix}
    L_d & -L_d \\
    -2L_d & -L_d
\end{bmatrix}
\begin{bmatrix}
    di_{s1}/dt \\
    di_{s2}/dt
\end{bmatrix}.
\] (3)

The model given by (1)-(2) or (3) can be extended to include the load model. To consider a particular type of load, the voltage-current load relationship must be provided and added to the model given by (1)-(2) or (3). The time derivative of the load current needed to compute \( u_t \) depends on the type of the load model.

**B. \( odq \) model**

The \( odq \) variables are determined from 123 variables by using the transforming equation given by

\[
y_{123} = A y_{odq}
\] (4)

with \( y_{123} = [y_1 \, y_2 \, y_3]^T \), \( y_{odq} = [y_o \, y_d \, y_q]^T \) and

\[
A = \sqrt{2} \begin{bmatrix}
    1 & 0 & 0 \\
    -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{\sqrt{3}}{2} \\
    -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & -\frac{\sqrt{3}}{2}
\end{bmatrix}.
\] (5)

In (5) \( A^{-1} = A^T \) and the vector \( y_{123} (y_{odq}) \) can be either grid, filter and load voltage vectors \( e_{s123}, v_{f123}, u_{123} \) \( (e_{sodq}, v_{fodq}, u_{odq}) \) or grid, filter and load current vector \( i_{s123}, i_{f123}, i_{123} \) \( (i_{sodq}, i_{fodq}, i_{odq}) \).

By using the transforming equation given in (4) and equations (1)-(2) or (3), the following \( dq \) model for representing the equivalent circuit of Fig. 2(a) can be obtained:

\[
e_{sd} - v_{fd} + u_d = R_t i_{sd} + L_d \frac{di_{sd}}{dt}
\] (6)

\[
e_{sq} - v_{fq} + u_q = R_t i_{sq} + L_d \frac{di_{sq}}{dt}
\] (7)

\[
u_d = R_f i_d + L_f \frac{di_d}{dt}
\] (8)

\[
u_q = R_f i_q + L_f \frac{di_q}{dt}
\] (9)

Fig. 2(b) presents the \( dq \) equivalent circuit for (6)-(9).

The homopolar equation obtained from (4) and (1)-(2) is given by \( v_f - \delta_f / \sqrt{3} \) = 0, because \( i_1 + i_2 + i_3 = 0 \) and \( i_1 + i_2 + i_3 = e_{s1} + e_{s2} + e_{s3} = 0 \). If \( v_f \) is chosen to be zero, then consequently \( \delta_{0n} = 0 \).

**IV. AFTER-FAULT MODEL**

**A. Three-phase model**

Fig. 1(b) illustrates the system when the phase 1 is open. The circuit equations for phase 1 open are derived from the

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**Fig. 1. System configurations.**

**Fig. 2. Equivalent circuit for the before fault system.** (a) Three-phase model. (b) \( dq \) model.
The resulting equations for phases 2 and 3 \((j = 2, 3)\) are

\[
\begin{align*}
e_{sj} - v_{fj} + u_{ej} &= R_si_sj + L_d \frac{di_{sj}}{dt} \\
u_j &= R_f u_{ej} + L_d \frac{di_{fj}}{dt}
\end{align*}
\]  

and for the phase 1

\[v_{m1} = e_{s1} - R_si_{s1} - L_d \frac{di_{f1}}{dt}; \quad i_f = 0\]

where \(v_{m1}\) is the voltage for phase 1 of the load referred to the point \(n\).

Note that the current \(i_{s1}\) cannot be controlled by \(v_{f1}\). Only the current \(i_{s2}\) and \(i_{s3}\) can be controlled. In the \(dq\) framework this means that only two currents among \(i_{s0}, i_{sd}\) and \(i_{sq}\) can be controlled. Moreover, since \(e_{s0} = 0\), for providing balanced power, even when leg 1 of the voltage source converter is lost, then the natural choice is to control the \(dq\) currents.

**B. \(dq\) model**

Using the transforming equation given in (4) associated to the phase 1 open, in which \(i_{s1} = i_{t1}\), it follows that:

\[
\begin{align*}
i_{s2} &= i_{t1} - \sqrt{3}/2i_{sd} + \sqrt{1}/2i_{sq} \\
i_{s3} &= i_{t1} - \sqrt{3}/2i_{sd} - \sqrt{1}/2i_{sq}
\end{align*}
\]

Under these conditions the \(dq\) model for unbalanced operation is given by

\[
\begin{align*}
e_{sx} - v_{fx} + u_{tx} + e_{tx} &= R_d i_{sd} + L_d \frac{di_{sd}}{dt} \\
e_{sz} - v_{fz} + u_{tz} &= R_d i_{sq} + L_d \frac{di_{sq}}{dt}
\end{align*}
\]

in which the new voltages \(y_z\) and \(y_x\) \((y\) indicates \(e, v_f, e_f))\) defined by

\[y_x = -\sqrt{1/6}(y_2 + y_3), \quad y_z = \sqrt{1/2}(y_2 - y_3), \quad (17)\]

with \(e_{tx} = \sqrt{2}/3(R_f i_{s1} + L_d di_{f1}/dt)\), have been introduced.

Fig. 3(b) presents the \(dq\) equivalent circuit. Note that, except for the unbalanced disturbance terms \(e_s, u_l\) and \(e_{tx}\) this model is balanced. It is possible to merge the disturbance into the model. This leads to a model having different parameters which depend on what phase is open.

The homopolar current is given by \(i_{so} = (i_{s1} + i_{s2} + i_{s3})/\sqrt{3}\) or by \(i_{so} = (\sqrt{3}i_{s1} - \sqrt{2}i_{sd})\) if (13)-(14) are introduced. The current \(i_{so}\) depends on \(i_{s1}\) (defined by the load) and \(i_{sd}\) (determined by (15)-(16)). This analysis also explains why \(i_{so}\) cannot be controlled by the filter.

The modeling for the case when the failure occurs in the another phase follows similar lines. The corresponding model is different from model presented above only with respect to the disturbance terms.

**V. CONTROL SCHEME**

The amplitude of the grid current is defined by capacitor \(dc\)-bus voltage control. To control the active filter, an appropriate model for designing the current control loop is required.

The before-fault control is achieved by controlling the grid current in phase with the corresponding grid voltage. The current controller can be either based on the phase component model given in (3) or based on the \(dq\) component model given in (6)-(9). The control variables are \(v_{d12}, v_{f12}, v_{d13}, v_{f13}\) and \(u_{f12}, u_{f13}\) are considered as disturbance terms that must be compensated by the controller. If a linear control is used it must compensate positive and negative sequence components [8] because \(u_{f12}\) and \(u_{f13}\) \((u_{f1d} and u_{f1q})\) are unbalanced as a consequence of the load unbalancing.

Figure 4(a) presents the block diagram for illustrating the control strategy based on phase components:

- Synch block generates the signals for synchronizing the grid reference current with the grid voltage.
- The capacitor voltage regulator \((R_c)\) determines the amplitude of the grid reference current.
- The current controllers \((R_{a12})\) determine the filter reference voltage.

The after-fault control is achieved by controlling the grid \(dq\) current in phase with the corresponding \(dq\) grid voltage. The current controller for phase 1 open is either based on the phase components model given in (10)-(11) or based on the \(dq\) components model given in (15)-(16). The control variables are \(v_{f2}, v_{f3}, v_{d2}, v_{d3}\) and \(e_{d2}, e_{d3}\) are considered as
disturbance terms that must be compensated by the controller. In this case the controller must compensate the unbalanced disturbance terms, besides the load unbalancing. Then, when a linear controller is used, it must compensate both positive and negative sequence components.

As discussed before the models for describing the dynamics of all the possible after-fault configurations differ only by the disturbance terms. This means that it is possible to have a controller with the same parameters for any phase open.

Figure 4(b) presents the block diagram for illustrating the after-fault control strategy based on phase components. In this case the block (T) represents the general transforming equation that takes into account in what leg the fault has occurred. For example, the equation (13)-(14) represents the specific implementation of this block when phase 1 is open.

VI. PWM SPACE VECTOR

The fourth leg shown in the scheme of Fig. 1(a) is inactive during normal operation. It has been added for backup and it is employed after the fault detection within the remedial strategy. In this case the standard space vector modulation technique can be employed to generate control signals for the converter switches. The modulation technique for the after-fault scheme [Figs. 1(b)] is described next.

For the scheme of Figs. 1(b) let us consider that the conduction state of the power switch is associated to binary variables q2, q3, q4, q5, q6, q7 and q8. Therefore, from now on binary ‘1’ will indicate a closed switch and binary ‘0’ an open one. Pairs q2-q6 and q4-q8 are complementary and as a consequence, q5 = 1 − q2, q6 = 1 − q3 and q8 = 1 − q4.

The system terminals voltages, v_f2 and v_f3, depend on the states of the power switches and may be expressed in terms of the previously defined binary variables q2, q3 and q4, as

\[ v_{f2} = v_{f20} + \delta_0 = (2q_2 - 1)\frac{E}{2} - (2q_4 - 1)\frac{E}{2} \]

\[ v_{f3} = v_{f30} + \delta_0 = (2q_3 - 1)\frac{E}{2} - (2q_4 - 1)\frac{E}{2} \]

where E is the dc-bus voltage.

The voltages supplied by the power converter to the system phases can be displayed in the space vector plane. This vector plane is defined such that v_f2 and v_f3 correspond to the real axis (Re) and the imaginary (Im) axis, respectively, that is:

\[ v_k = v_{f2} + jv_{f3} \text{ for } k = 0, 1, 2, ..., 8 \]  

as shown in Fig. 5. The instantaneous voltage vectors generated by the converter are listed in Table 1, for the binary states of the power switches.

There are eight vectors: four vectors with amplitude E (v_1, v_3, v_4 and v_6), two vectors with amplitude \(\sqrt{2}E\) (v_2 and v_5) and two null vectors (v_0 and v_7), as shown in Table 1 and Fig. 5. These vectors define six sector K = 1, 2, ..., 6. The phase-voltage v_f2 and v_f3 assume only three different values: E, 0, or -E.

![Fig. 4. Block diagram for the system controller.](image_url)
Let $\mathbf{v}^*$ represent the reference voltage to be synthesized by the converter within one cycle time of length $T$. According to the space vector technique [9], the reference vector located in sector $K$ is synthesized by using the zero vectors and the two adjacent vectors that define the sector. Then, for the sector $K$, it can be written that

$$\mathbf{v}^* = \mathbf{v}_m \frac{t_m}{T} + \mathbf{v}_{m+1} \frac{t_{m+1}}{T} + \mathbf{v}_0 \frac{t_0}{T} + \mathbf{v}_7 \frac{t_7}{T} \quad (19)$$

with the time positive weights for each vector $t_m$, $t_{m+1}$, $t_0$, and $t_7$ restricted to $T = t_m + t_{m+1} + t_0 + t_7$ ($m = 0, 1, 2, ..., 8$ and $m + 1 = 1$, if $m = 6$).

Note that in steady state, $\mathbf{v}^*$ does not describe a circle, as in the $dq$ plane for a balanced two-phase system.

By using (18), then $\mathbf{v}^* = \mathbf{v}_{j2}^* + j\mathbf{v}_{j3}^*$ and since $\mathbf{v}_0 = 0$ and $\mathbf{v}_7 = 0$, it follows from (19) that

If $K = 1 \Rightarrow t_1 = (\mathbf{v}_{j2}^* - \mathbf{v}_{j3}^*) T_E$; $v_2 = v_{j3}^* T_E$

If $K = 2 \Rightarrow t_2 = v_{j2}^* T_E$; $v_3 = (v_{j3}^* - v_{j2}^*) T_E$

If $K = 3 \Rightarrow t_3 = v_{j3}^* T_E$; $v_4 = -v_{j2}^* T_E$ \quad (20)

If $K = 4 \Rightarrow t_4 = (v_{j3}^* - v_{j2}^*) T_E$; $v_5 = -v_{j3}^* T_E$

If $K = 5 \Rightarrow t_5 = -v_{j2}^* T_E$; $v_6 = (v_{j2}^* - v_{j3}^*) T_E$

If $K = 6 \Rightarrow t_6 = -v_{j3}^* T_E$; $v_7 = v_{j2}^* T_E$

where $T_E = T/E$.

Given the magnitudes of the components of vector $\mathbf{v}^*$, i.e., $v_{j2}^*$ and $v_{j3}^*$, the sector can be determined in the following way

If $v_{j2}^* > 0$, $v_{j3}^* > 0$, $v_{j2}^* > v_{j3}^*$ $\Rightarrow$ $K = 1$

If $v_{j2}^* > 0$, $v_{j3}^* > 0$, $v_{j2}^* \leq v_{j3}^*$ $\Rightarrow$ $K = 2$

If $v_{j2}^* < 0$, $v_{j3}^* > 0$ $\Rightarrow$ $K = 3$ 

If $v_{j2}^* < 0$, $v_{j3}^* < 0$, $v_{j2}^* < v_{j3}^*$ $\Rightarrow$ $K = 4$

If $v_{j2}^* < 0$, $v_{j3}^* < 0$, $v_{j2}^* \geq v_{j3}^*$ $\Rightarrow$ $K = 5$

If $v_{j2}^* \geq 0$, $v_{j3}^* < 0$ $\Rightarrow$ $K = 6$ \quad (21)

The values for $t_0$ and $t_7$ are not defined. They can be chosen by introducing the apportioning factor $0 \leq \mu \leq 1$

$$t_0 = \mu(T - t_m - t_{m+1}); \quad t_7 = (1 - \mu)(T - t_m - t_{m+1}) \quad (22)$$

Then, the modulation technique for the scheme presented in Fig. 1b can be implemented by executing the following steps:

i) Given $v_{j2}^*$ and $v_{j3}^*$, determine $K$ from (21) and $t_m$ and $t_{m+1}$ from (21).

ii) Given $\mu$ compute $t_0$ and $t_7$ from (22).

The modulation strategy for the other phase open follows similar steps.

VII. SIMULATION RESULTS

Figure 6 presents the grid power ($p_g$) and active filter power (low-pass filtered) ($p_f$) [Fig. 6(a)], the grid and filter phase currents [Fig. 6(b)], and the grid $dq$ voltages and currents [Fig. 6(c)] for the system, before and after the fault occurrence (leg 1 open). The system parameters are: $R_y = 0.1 \, \text{pu}$, $X_y = 0.38 \, \text{pu}$, $R_f = 0.05 \, \text{pu}$, $X_f = 0.2 \, \text{pu}$. The current load is given by following composition: active (0.5 pu) + reactive (0.3 pu) + negative sequence (0.2 pu). The grid voltage amplitude is 1 pu. The fault has occurred at $t = 0.03$s, when both switches of leg 1 are open. It can be noted that before and after the fault the $dq$ currents are controlled quite well. On the other hand the grid power is nearly continuous, except for a small ripple introduced by the switching of the converter, and the average power of the active filter is zero.

VIII. EXPERIMENTAL RESULTS

In the experimental set-up, the controllers were implemented by software in a Pentium II - 266 MHz micro-computer, equipped with dedicated plug-in boards, with $h = 200\mu$s, and the switching frequency of the VSC was $5k$Hz. A positive-negative sequence controller is employed [8].

Figs. 7 show the reference and actual $dq$ currents for the system before and after the fault occurrence, for the positive-negative sequence controller and the positive sequence controller operating at $60$ Hz. The fault was caused at $t = 0.015$s, when both switches of leg 3 are open. Except for the transient caused by the fault, the controller tracks quite well the current.

IX. CONCLUSIONS

This paper has demonstrated that it is possible to provide fault tolerant properties for a three-phase shunt active power filter by adding a fourth leg to the filter converter. The fourth leg is connected to the grid neutral, is idle during normal operation and is employed when a fault in one of the three other legs is detected. This control of
this extra leg is part of the remedial strategy for compensate for the fault. Since the after-fault configuration is an asymmetric system it was necessary to develop a suitable model and control strategy. It has been demonstrated that it is possible to maintain power balanced operation of the grid source even when one of the inverter legs is lost. However, it is not possible to provide full fault compensation since the configuration of the active filter when the fault occurs does not permit to control the homopolar components. The proposed solution extends the functionality of the system and, consequently, increases its reliability.

References