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RELIABILITY ANALYSIS IN A FAULT TOLERANT CONTROL STRATEGY DEDICATED TO ACTIVE POWER FILTER

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Abstract: The aim of Fault Tolerant Control (FTC) is to preserve the ability of the system to reach performances as close as possible to those which were initially assigned to it. The main goal of this paper is to develop a FTC system, based on reliability analysis dedicated to an active power filter. Once a fault has been detected and isolated, all possible structures of the system that preserve pre-specified performance are analyzed and the highest reliability indicate the optimal structure.

Keywords: Fault Tolerant Control, System Reliability, Active power filter, Control Reconfiguration.

1. INTRODUCTION

In most conventional control systems, controllers are designed for fault-free systems without taking into account the possibility of fault occurrence. In order to overcome these limitations, modern complex systems use sophisticated controllers which are developed with fault accommodation and tolerance capabilities, in order to meet reliability and performance requirements. The Fault Tolerant Control (FTC) system is a control system that can maintain system performance closely to the desirable one and preserves stability conditions, not only when the system is in fault-free case but also in the presence of faulty component, or at least ensures degraded performances which can be accepted as a trade-off. FTC has been motivated by different goals for different applications; it could improve reliability and safety in industrial processes and safety-critical applications such as flight control and nuclear power plant operation (Zhang and Jiang, 2003).

Various studies on FTC are based on hardware or analytical redundancy. The hardware redundancy technique consists of switching from the failed part of the process to another achieving the same task. The analytical redundancy is an alternative to solve the FTC problem avoiding the disadvantages of the hardware redundancy such as high cost and space. In this paper, the main goal is to determine the "best" reconfiguration structure among various with or without redundant components.

Generally, Fault Tolerant Control systems are needed in order to preserve the ability of the system to achieve the objectives that has been assigned when faults or failures occurred. (Staroswiecki and Gehin, 2001) proposes a terminology on fault tolerant control problems. The main goal of FTC is to increase system's reliability. Some publications have introduced reliability analysis for fault tolerant control systems. Also (Staroswiecki *et al.*, 2004) have proposed a sensor reconfiguration based on physical redundancy where the reliability analysis provided some information in order to select the optimal redundant sensors. In, (Wu, 2001a), (Wu, 2001b), (Wu and Patton, 2003) Markov models are used to dictate the system reliability where it's supposed that the sub-systems take two states intact (available) or failed (unavailable).

In this paper, a FTC strategy, based on reliability analysis dedicated to an active power filter is considered. The reliability of power electronic equipments becomes extremely important in industry applications (Bobbio, 1990), (Bobbio, 1991). The fault mode behaviour of static converters, protection and fault tolerant control of voltage source inverter systems has been covered in a large number of papers. Most of them are focused on induction motor drive applications. According to (El Brouji *et al.*, 2006), various shunt three phase active filter topologies or reconfiguration structure can be considered in faulty cases with a classical hardware redundancy or suitable structures. Based on the highest reliability criterion, the FTC method provides an optimal structure in order to achieve desired objectives closed as possible as nominal ones.

The paper is organized as follows. Section 2 is dedicated to define the associated standard problem of FTC. Section 3 is devoted to the three legs shunt

active filter topologies in fault free and faulty cases. Section 4 concerned to the reliability computation according to the various topologies. A simulation example is considered in Section 5 to compare the various topologies. Finally, concluding remarks are given in the last section.

2. PROBLEM STATEMENT

Let us define the control problem by the triplet $< \gamma_g, C, U >$, in the spirit of (Staroswiecki and Gehin, 2001), where:

- γ_g Global objectives
- C A set of constraints given by the structure of system S, and the parameters of closed-loop system θ
- U A set of control laws

In fault-free case, this problem could be solved by defining a control law $u \in U$, such that the controlled system achieves the global objectives γ_g under constraints whose structure S and parameters θ are equivalent to design controllers of all sub-systems used by the structure and to define their references to achieve γ_g. It is assumed that nominal global objectives γ_g^{nom} are achieved under the nominal control law u_{nom} and the nominal structure S_{nom} which uses some sub-systems. The fault occurrence is supposed to modify the structure S_{nom} for which the objectives can be or can not be achieved under a new structure.

The fault tolerant control problem is then defined by $< \gamma_g, C, U >$, which has a solution that could achieve γ_g^{nom} by changing the structure, parameters and/or control law of the post-fault system (which results in the disconnection or replacement of faulty sub-systems). In some cases, no solution may exist, and then global objectives must be redefined to the degraded ones, denoted as γ_g^d.

Under assumptions that there exist several structures S_m $m = (1, \ldots, M)$, the problem statement is formulated by the following question: how to choose the optimal structure in the sense that for a given criterion J the chosen structure can maintain the objectives γ_g^{nom}? An answer will be provided in the following section based on reliability analysis dedicated to an active power filter. Compared to (Guenab *et al.*, 2005), and due to the specific application, the reliability analysis will be studied off-line.

3. SHUNT ACTIVE FILTER TOPOLOGIES

Fig. 1 presents a classical three-leg shunt power active filter which represents the nominal structure S_{nom}. The nominal global objectives γ_g^{nom} is to determine the current harmonic reference to be generated by the active filter as proposed by (Akagi et al., 1983) using classical active and reactive power method.

It is composed by a grid (esi for i = {1, 2, 3}), a non-linear load and a voltage source converter. The load is a three-phase diode rectifier feeding an (R, L) series load. The grid is supposed to be balanced with equal series resistances r_s and inductances l_s for each phase. The static converter is a voltage source inverter with equal series resistances r_f and inductances l_f for each phase.

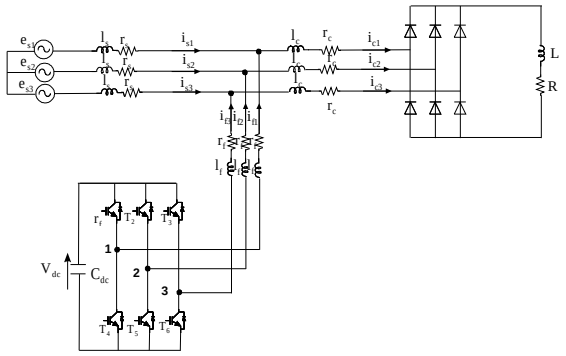


Fig.1: Classical three-leg shunt active filter: S_{nom}.

The output currents of the shunt active filter are controlled to provide reactive power and harmonic currents generated by the non-linear load to ensure filtering. The capacitor C_{dc} of the DC filter side is an energy storage capacity. According to (El Brouji *et al.*, 2006), two fault tolerant shunt active filter schemes are more particularly studied, i.e. $m = (1, \ldots, M = 2)$. These structures use connecting and isolating devices; they allow reconfiguring the power converter topology after fault detection of one of the semi-conductor devices. These two fault tolerant filter structures are based on the classical and healthy structure presented in Fig. 1.

The first one, S_1 presented Fig. 2, is a three legs topology. The three legs are used in healthy condition. This structure includes bi-directional devices T_{rk} (k = {1, 2, 3}) (triacs in this case to simplify control) allowing the connection between the grid (for the phase number *k* having a faulty

semiconductor device) and the middle point O of the capacitor C_{dc}.
Under this topology, if one of the semiconductor T_i or its associated switch driver is faulty, the leg including T_i could be isolated and the point *k* will be directly connected to the middle point O by switching on the triac T_{rk}. Consequently, the fault tolerant topology is a two legs structure with faulty phase connected to O.

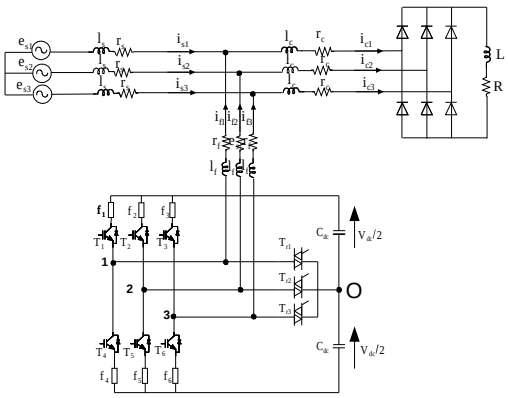


Fig.2: Fault tolerant three-legs shunt active filter: S_1.

The second structure S_2, is based on hardware redundancy: a four-leg filter topology. As presented in Fig. 3, the fourth leg composed of devices T_7 and T_8 is a redundant leg. This leg will replace if necessary the faulty one of the three other legs. Bidirectional devices allow connecting the faulty phase number *k* to the leg constituted by T_7 and T_8.

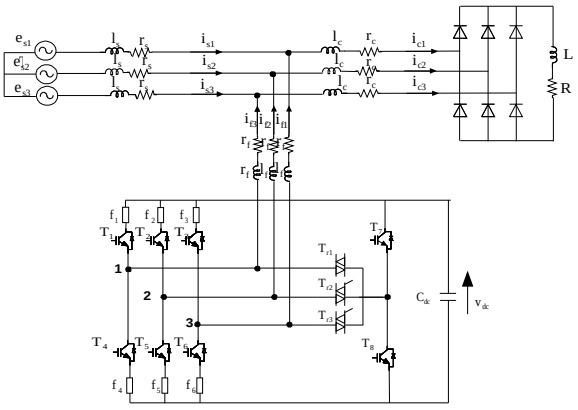


Fig.3: Fault tolerant four-legs shunt active filter: S_2.

The same shunt active filter control is available for three-legs and two-legs structures as illustrated in Fig. 4. The major advantage of the control law $u \in U$ is to be suitable for the set of fault-free S_{nom} and faulty S_m $m = (1,\ldots,M)$ structures.

According to this control scheme, the same reference voltage V_{dcref} can be used for the Fault tolerant four-legs shunt active filter. The reconfigured structure is the same as in fault-free case.

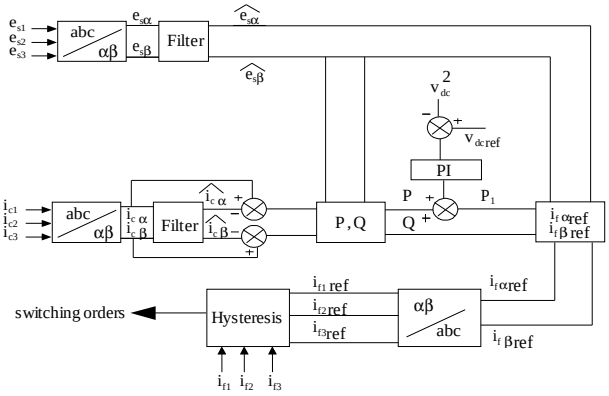


Fig. 4 : Block diagram of the control system.

However, concerning the fault tolerant three-leg shunt active filter, illustrated in Fig. 2, the structure is initially composed of a three legs and becomes a two legs topology after reconfiguration. The V_{dcref} value changes after reconfiguration simultaneously with converter reconfiguration. The new V_{dcref} should be determined twice greater than in fault-free case. Increasing the V_{dcref} allows decreasing the frequency of T_i commutations.

As presented in this section, according to (El Brouji *et al.*, 2006), various shunt three phase active filter topologies or reconfiguration structure can be considered in faulty cases with a classical hardware redundancy or suitable structures with $\gamma_g = \gamma_g^{nom}$ for the same control law $u \in U$, $\forall\, S_m$ $m = (1,\ldots,M)$ structures. Consequently, the fault tolerant control problem $< \gamma_g, C, U >$ could summarized by determined the optimal structure with the highest reliability.

4. MARKOV CHAIN MODEL OF RELIABILITY

Representing system failure in a probabilistic way is attractive because it naturally accounts the uncertainty. To make such representation, the process behaviour is considered as a random variable that takes its values from a finite state space corresponding to the possible process states. Deterioration can be modelled by a discrete time stochastic process. In the case of finite or countable state space, Markov processes can be represented by a graphic called Markov Chain (Ansell, et al., 1994).

Markov chain models a sequence of random variables $\{X_k,\ k = 0, 1, 2...\}$ for which the Markovian property is held. Let $\{s_1,...,s_M\}$ be a finite set of the possible mutually-exclusive states of each X_k. The probability distribution over these states is represented by the vector $p(X_k)$:

$$p(X_k) = [p(X_k = s_1), ... p(X_k = s_m), ..., p(X_k = s_M)]$$
$$\text{with } \sum_{m=1}^{M} p(X_k = s_m) = 1 \quad (1)$$

In this paper, only constant failure rates are considered. Homogenous Markov chains are used for this case because of the stationarity of transition probabilities. In such model, transition probabilities are time invariant and depend only on values states:

$$p_{ij} = p(X_{k+1} = s_i \mid X_k = s_j) = p(X_{k+2} = s_i \mid X_{k+1} = s_j) \quad (2)$$

In a homogeneous discrete-time MC, the transition matrix $\mathbf{P}_{MC}$ between the states is defined from failure rate parameters. For instance let us consider a system (Fig. 5) with two states {1,2}, then:

$$\mathbf{P}_{MC} = \begin{bmatrix} 1 - p_{12} & p_{12} \\ 0 & 1 \end{bmatrix} \quad (3)$$

Where $p_{12} \cong \lambda \Delta t : \lambda$ presents a constant failure rate and Δt is the time interval. The probability p_{12} can be interpreted as the probability that the component fails after the time Δt.

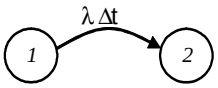


Fig. 5. Markov Chain for modelling deterioration model

Given an initial distribution over states $p(X_0)$, the probability distribution over states after k stage $p(X_k)$ is obtained from the Chapman-Kolmogorov equation:

$$p(X_k) = p(X_0) \prod_{i=0}^{K} \mathbf{P}_{MC} \quad (4)$$

Assuming that $i \in \{0...l\}$ represents the functioning states, system reliability is defined as:

$$R(k) = \sum_{i \in \{0...l\}} p(X_k = s_i) \quad (5)$$

The use of classic MC to model deterioration in systems needs to enumerate all possible states which lead sometimes to a huge transition matrix.

5. RESULTS AND COMMENTS

5.1 Performances analysis

This simulation results are obtained with Saber CAD simulator for the two fault tolerant topologies. General simulation parameters are equal to:
- Grid : 230V, 50 Hz
- Non-linear load : R = 0,6 Ω, L = 2,5 mH,
- l_c = 15µH, r_c = 0,4 mΩ
- Filtering capacitor : C_{dc} = 17,6 mF.

Depending on the studied topology, hysteresis band value and the V_{dcref} are defined in order to achieve a THD value below 5%.

Fig. 6 presents results in an open circuit case, the fault of the bottom switch of the leg number 3 is introduced at t=200 ms for three-legs shunt active filter structure S_1. The value of the capacitor voltage reference is set to 800 V before the fault in the three-legs topology and set to 1300 V after the fault in the two-legs topology reconfiguration. The value of l_f is 150µF and the hysteresis band equal to 20 A. The proposed fault tolerant system preserved the main performance features after fault compensation. More, the mean switching frequency is equal to 7 kHz before fault and equal to 9.5 kHz after fault.

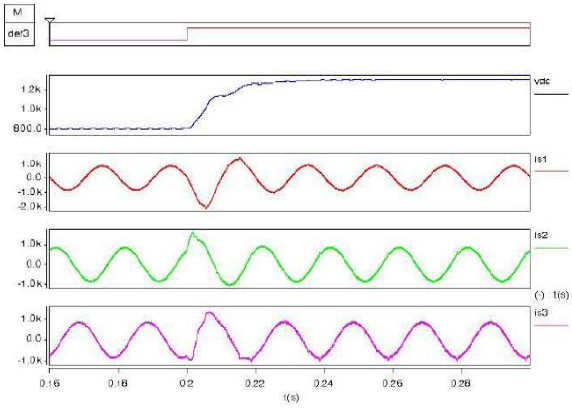


Fig. 6. Current and voltages dynamic behaviour for S_1

Fig. 7 presents results in a short circuit case, the fault of the bottom switch of the leg number 3 is introduced at t= 200 ms for four-legs shunt active filter structure S_2. The value of the capacitor voltage reference is set to 700V. The value of l_f is 150µF and the hysteresis band is equal to 20 A. Performances are the same as the previous one.

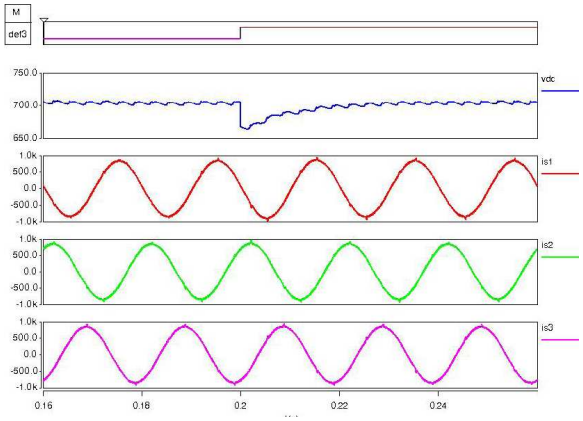


Fig. 7. Current and voltages dynamic behaviour for S_2

According to the dynamic behaviour of the current and voltages system, it can be noticed that with a classical hardware redundancy or suitable structure (i.e. $\forall S_m \quad m=(1,\ldots,M)$ structures), the reconfigured structure provides a global objective $\gamma_g = \gamma_g^{nom}$ for the same control law $u \in U$.

5.2 Reliability analysis

Due to the fact that the number of commutations decrease when the voltage increase, consequently, the failure rates of T_i decrease: $\lambda_{Ti(350V)} \geq \lambda_{Ti(800V)}$. However, the failure rate of the capacitor increase with the voltage: $\lambda_{Cdc(350V)} \geq \lambda_{Cdc(700V)}$.

The following table presents the value of the failure rate according to the voltage and also the Mean Time To Failure (MTTF). It can be noted that the variable α represents the switched failure probability of triacs T_{rk}.

	Failure rates	MTTF (h)
$\lambda_{Ti(350V)}$	1.67 E-05	60 000
$\lambda_{Ti(800V)}$	1 E-05	100 000
$\lambda_{Cdc(350V)}$	0.5 E-05	200 000
$\lambda_{Cdc(700V)}$	0.67 E-05	150 000
$\lambda_{Cdc(800V)}$	1 E-05	100 000
α	12.5 E-05	8 000

(All these values are not real parameters)

Table 1: Failure rates of the elementary components

Based on section 4, the fault-free structure and the two reconfigured structures are represented as Markov Chain models as illustrated in the figures 8, 9 and 10 (for simplicity Δt is considered equal to *1*). The state s_1 corresponds to the fault-free state. If a failure occurs on capacitor or T_i, the system is out of order which corresponds to the state s_2 for the structure S_{nom} (see Fig. 8.) or s_3 for the reconfigured structures. The state s_2 represents the state of the system for the reconfigured structures with the presence of a failure on T_i. It should be noted that the Fig. 9 and 10 include the commutation ability of the three and four legs shunt solutions.

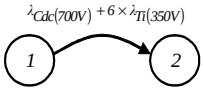


Fig. 8. Markov Chain for modelling the system with the nominal structure S_{nom}.

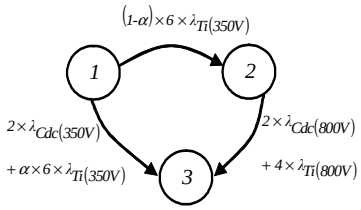


Fig. 9. Markov Chain for modelling the system with three legs shunt S_1.

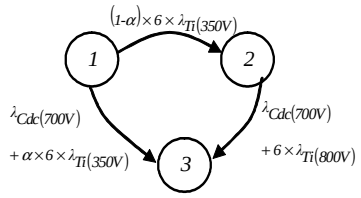


Fig. 10. Markov Chain for modelling the system with four legs shunt S_2.

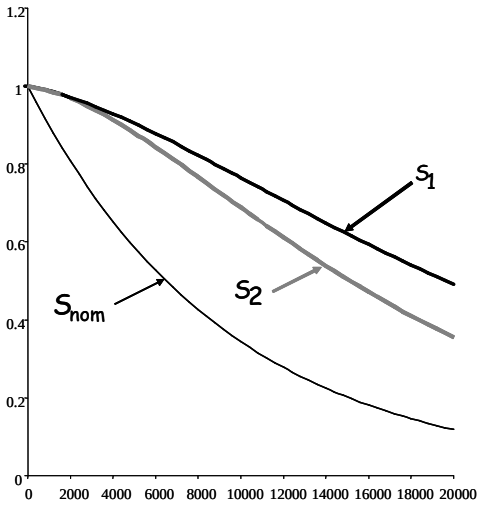


Fig. 11. Reliability computation.

The reliability curves of the systems are shown in Fig. 11. With a hardware redundancy or a suitable structure, the reliability is greater than a nominal structure. Neverthless, in regard with the parameters, defined in Table 1, the three-legs shunt system is less preferment in the beginning but become more interesting in a long horizon. Consequently, according to the performance requirements, it is convenient to get the optimal structure as the three-legs topology.

Other scalar criteria such as MTTF could be evaluated to choose the structure with the highest reliability. Thank to the Markov model, the MTTF is computed and equal to 9 375 h for the initial structure, 18 162 h for the four legs shunt structure, 24 240 h for the three legs shunt structure. It should be appreciated that the analysis of the MTTF confirms the previous choice: the optimal structure is the three-legs topology (according to Table 1).

6. **CONCLUSIONS**

In this paper, a Fault Tolerant Control strategy dedicated to an active power filter which incorporates reliability analysis into the reconfigurable control structure selection has presented. Once a fault occurred, the proposed FTC strategy will switch to the suitable structure. The selected structure will guarantee an optimal performance of the reconfigured system according to the "highest" reliability in order to ensure the dependability of the active power filter system and the "human safety".

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