UPQC reliability analysis

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***Abstract*— In this paper an analysis of the line interactive device UPQC (Unified Power Quality Conditioner) from a reliability point of view is carried out. A brief description of its topology points out the components constituting it, such as the static transfer switch, the converters, the energy storage unit and the input static switch. The device normal and fault conditions are studied in order to define the load voltage magnitude starting from the operational states of the components: we can see that this relationship depends significantly on the compensator topology and the protection system. The series unit protection system is defined and verified by means of numerical simulation.**
The stochastic process describing UPQC behaviour is studied, in the hypothesis that state durations, namely life and repair times, are exponentially distributed. Assuming stochastic independence for all the components, the whole system follows a continuous time Markov process with a finite state space. System analysis is then performed in stationary conditions, making it possible to estimate the MTBF (Mean Time Between Failures) and the MTTR (Mean Time To Restoration) of the output compensator voltage. Finally load voltage MTBF is computed taking also a mechanical bypass switch into account.

I. Introduction

The recent, ever more widespread use of power-electronic devices has increased the degree of reliability to be expected of electrical systems. Special importance attaches to the reduction in voltage sags and outages, which are usually the cause of frequent malfunctioning in industrial processes. For some time now static continuity units have been in use to obtain a stable, continuous and sinusoidal voltage on the load and to achieve sinusoidal current absorption with a unity power factor. Together with traditional double conversion UPS, line interactive ones are being currently developed, which makes it possible to improve efficiency and limit plant costs [1]. With this devices, the load is supplied with conditioned power via a parallel connection of the A.C. network and the compensator inverter: thus, the frequency of the voltage on the load necessarily depends on the network frequency (synchronous coupling). Of the possible UPS line interactive devices already suggested in technical literature, this paper deals with the UPQC (Unified Power Quality Conditioner) [2].

The application of such device makes a comparison from a reliability point of view a matter of some importance. In order to carry out this evaluation, a detailed study of the device behaviour under various fault conditions is a prime requirement. The operation of the protection devices must be considered. An analysis of the stochastic process, which describes the system evolution with time, follows below.

In the analysis, reference is made to the Italian TT distribution system.

A. The device

The UPQC, shown in fig.1, consists of two converters, one of which is inserted in parallel with the load, while the other is in series with the power supply line employing an injection transformer. It also comprises a static transfer switch, a static input interruption device and an energy storage unit.

In fig. 1, the symbol *VSI* denotes the sub-system consisting of the 3-phase IGBT bridge and of the *L-C* filter needed to filter out the voltage and current harmonics at the switching frequency.

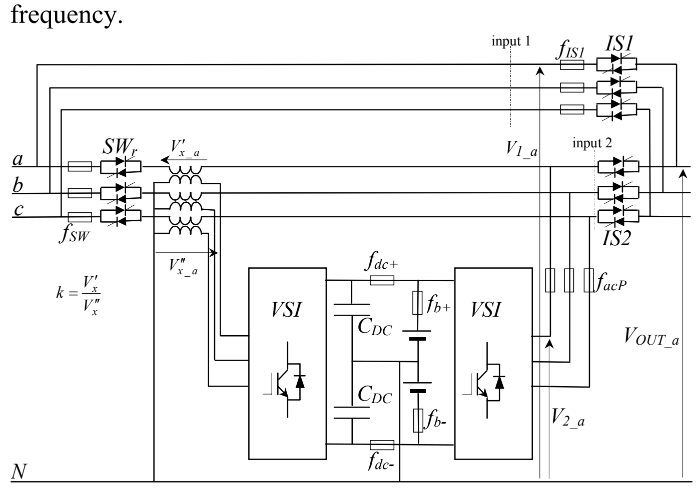

Fig. 1. UPQC with protection devices. Voltages V_1, V_2 and V_{OUT} pertaining to phase "a" of the converter and the turn ratio k of the injection transformer are also shown.

In the static transfer switch, the circuit elements and electrical values referring to the side towards the bypass are indicated with suffix 1 (*IS1*, f_{IS1}, V_1) while those towards the inverter are indicated with suffix 2 (*IS2*, f_{IS2}, V_2).

The function of the static transfer switch is to transfer the load without interruption from the inverter output to the mains in case the inverter section fails or overloads.

This device is capable of supplying the load with a voltage which is sinusoidal, symmetrical and of a constant RMS value, whilst absorbing from the mains a current which is sinusoidal, at a unity power factor and balanced by achieving a synchronous coupling to the mains. The unit in parallel is controlled as a voltage generator, while that in series as a current generator.

Operation at unity power factor can be achieved in various ways, making each converter exchange both active and reactive power with the mains. In order not to vary the charge status of the storage device, the active powers absorbed by the two units must be equal and opposite, hence obtaining only a power transfer in the D.C. section.

The choice of compensation strategy and of the injection transformer turns ratio is influenced by the following considerations:

-device losses, which, as a first approximation, are proportional to currents circulating in the two converters;

-phase shifting between mains and load voltages, which might cause a heavy operation condition of the static transfer switch;

-load sensitivity to voltage phase shifting[3];

-supply voltage range ($V_{comp}^{\min} < V_{mains} < V_{comp}^{\max}$) for which compensation is obtained without islanding operation. $V_{comp}^{\min}$ has been assumed to be 70% of the nominal voltage, because, in public mains systems, the most frequent disturbances consist of voltage sags with the residual voltage exceeding 70%, as shown by IEC studies.

The choice of the transformer turn ratio determines the maximum voltage $V_x^{\max}$ which can be injected by the series unit into the distribution line.

For voltages out of the previous range or when some of the device components are faulty, the load can be supplied in islanding operation by the shunt unit, drawing energy from the storage system.

B. The protection system

UPQC protection devices, shown in fig. 1, are:

-overcurrent protection devices, placed at the A.C. input of the compensator (static switch SW_r and its series protection fuses f_{SW});

-circuit-breaker or fuse for battery protection (f_b);

-overcurrent protection device placed at the D.C. input to the parallel unit (fuses f_{dc} and f_b);

-system for controlling and limiting the current supplied by the parallel unit and by the series one;

-desaturation circuits for the protection of IGBTs from short circuit currents;

-fuses protecting the thyristors in the static transfer switch: f_{IS1} at the by-pass circuit input, set of fuses f_{acP} and of the static switch SW_r at the UPQC input. Fuses on the standby line must handle a short circuit current of 10 times the nominal load current during 1-5 cycles to obtain coordination with the load protection [4]. Fuses f_{acP} must blow also for the weak short circuit current furnished by the inverter.

II. Protection Issues for Series Converter

In this paper, the term "primary winding" of the injection transformer is used to denote the winding placed in series with the line.

The behaviour of the protection system of the shunt unit and of the transfer static switch has already been described in the technical literature [4]. When an excessive current is detected, either the fuses blow or the inverter output current limitation system comes into play.

The protection philosophy based on limiting (or, at most, interrupting) the inverter current upon detecting an overcurrent condition, has to be carefully studied in the case of the series unit.

For faults stemming from a short circuit on the secondary of the injection transformer or in filter capacitors, the VSI enters its limiting condition. A short circuit in one or more IGBT of the converter of the series unit causes fuse f_{dc} to blow. In both the above cases, line current control is lost, but in either case a reclosing path for secondary currents is assured until the opening of the static switch SW_r.

However, a critical situation arises in the case of overcurrents due to a short circuit on the primary side of the injection transformer. The worst situation, which occurs when the short circuit appears downstream the injection transformer, will be studied.

The turns ratio k of the injection transformer shown in fig. 1 is lower than unity to improve the compensator efficiency. Because of this, the transformer injects, in series with the line, a voltage V_x', whose RMS value does not exceed $k \cdot V_n$. Hence, in the case being studied, it is not capable of containing the primary short circuit current. The limitation of inverter current, not accompanied by a similar limitation of primary current, causes an unbalance in the magneto-motive forces in the injection transformer. This is liable to be over-magnetised, generating damaging secondary side overvoltages [5] until the opening of the protection device placed in series with the line (SW_r static switch).

This dangerous situation in the UPQC is avoided, as, during the brief period before the operation of the static switch, the free-wheeling diodes of the series unit converter and the D.C. section capacitors provide a secondary current path where the current required by the primary can circulate. In addition, at this stage, the low saturation characteristic of the transformer increases the current ratio error and so reduces the amplitude of the secondary current [6].

During this transient, the VSI of the series unit acts as a diode rectifier, charging the D.C. bus voltage.

A detailed study of this fault transient is needed to determine the sizing of the components necessary in order that they can carry out their protection function.

A model has thus been set up on a computer comprising the electrical network and the part of the device under study (series converter, injection transformer and input static switch SW_r). These are shown in fig. 2, while the electrical parameters are listed in Table 1.

The transient shown in fig. 3 is the result of a short circuit immediately downstream the injection transformer, starting from the nominal voltage condition of the mains.

It can be seen that, immediately after the fault occurring at *0.03s*, the primary overcurrent is balanced by a secondary overcurrent which circulates in the inverter. At this stage, there is an increase in the D.C. section voltage.

Later on, the injection transformer reaches its saturated condition, which makes the voltage disappear from its terminals. This causes the following:

-increase in the primary overcurrent, as the transformer is incapable of injecting any voltage in series with the line;

-disappearance of the voltage across the filter capacitors, and hence of the current absorbed by the inverter.

TABLE 1

ELECTRICAL PARAMETERS OF SYSTEM UNDER STUDY

Mains	Rated voltage	230/400V
	Short circuit power	10MVA
Load	Rated power	50kVA
	Power factor	0.8
Series compensator	Rated voltage	230/400V
	Rated power	20kVA
	D.C. section capacitors C_{DC}	60mF
Injection transformer	Rated power	20kVA
	Turn ratio k	0.4
	Short circuit impedance [%]	5%
	Short circuit losses	500W
	Exciting current [%]	5%
	Core losses	170W

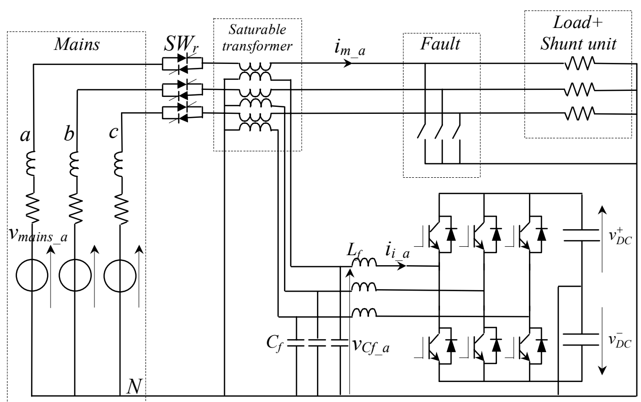

Fig. 2. Section of the plant taken into consideration during the study of the short circuit transient

In the case of the inverter, the protection function does not call for a substantial increase in the current-carrying capacity of the free-wheeling diodes, because the duration of the current pulse is short. In the specific case of the IGBT module BSM50GB120DLC [7], chosen on the basis of nominal operation (nominal DC-collector current *50A*) the diodes can withstand the short circuit transient (the I^2t value of the diodes is equal to $430A^2s$, while the transient produces only $200A^2s$). In addition, there was no need to increase the voltage rating of the valves, given the stability of the D.C. section voltage obtained by installing C_{DC} capacitors of *60mF*.

On the other hand, the capacitor of the *L-C* filter requires an increase in its voltage rating to be able to carry out its protection function, as shown in fig. *3.d*.

In this approach to protection, two features are particularly important:

-speed and, above all, reliability in the operation of the line protection devices, so as not to have to increase the capacity of the free-wheeling diodes excessively. For this reason, a fuse has been placed in series with the input static switch SW_r, which blows if a thyristor failure occurs;

-absence of overcurrent protection devices (circuit-breaker or fuse) between the DC section capacitors and the injection transformer. If used, their opening would produce a high overvoltage on the transformer secondary.

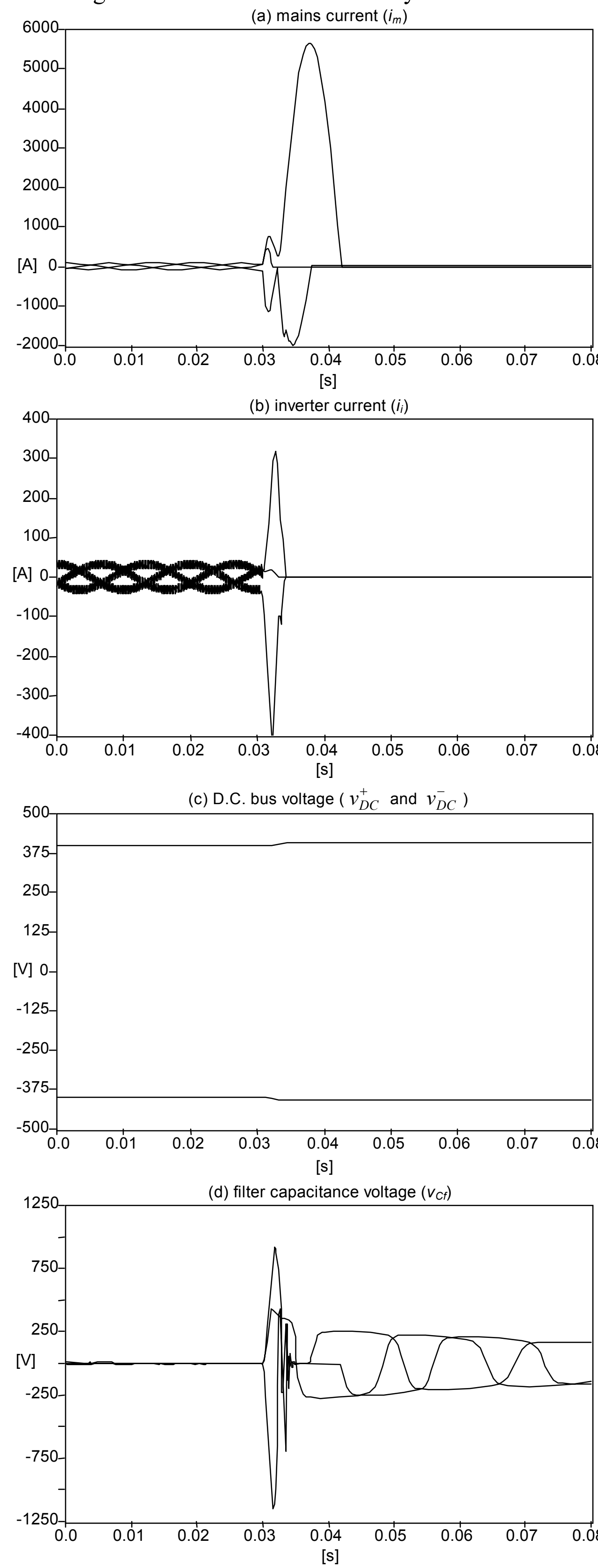

Fig. 3. Waveshapes of some electrical variables during a short circuit immediately downstream the injection transformer.

III. Normal and Fault Conditions: The Fault Tree

Anomalous behaviour of components can be caused by faults in the power circuit or in the control logic. In the case of controlled semiconductor devices, faults in the firing circuit are considered to be of the same kind as those in the power circuit. This is because, for the purpose of this analysis, they cause the same effects, namely reducing the element to either an open circuit (O.C.) or a short-circuit (S.C.). On the other hand, faults in the control logic include all the phenomena which result in the generation of "ON" or "OFF" signals at the wrong times. Hence, the following faults have been considered:
-in the semiconductor devices: S.C. or O.C.;
-in the component logic control;
-short circuits in either the A.C. or the D.C. section.
The analysis of fault conditions has been carried out separately for the static transfer switch and the compensator by constructing their fault tree. A fault tree illustrates the states of the system components, defined as *basic events*, and the connections between these basic events and the event being studied, defined as *top event*.

A. *Static Transfer Switch*

Table 2 shows the operational states determined for the static transfer switch.

TABLE 2
STATIC TRANSFER SWITCH OPERATIONAL MODES

Operational modes	*Typical cause*
SW_1: correct operation	
SW_2: IS1 thyristor short circuit	• thyristor power circuit failure • thyristor firing circuit failure
SW_3: IS2 thyristor short circuit	
SW_4: IS1 thyristor open	
SW_5: IS2 thyristor open	
SW_6: control failure	• control logic failure

An analysis of the action of static transfer switch protection devices has made it possible to determine the fault tree referring to the magnitude of V_{OUT} voltage, as a function of thyristor operational modes and of the input voltages (see fig. 4).
A short-circuit in a thyristor of IS1, together with an out-of-limits condition of the mains voltage causes the loss of the load. The weak short circuit current from the inverter is not capable of blowing the fuse f_{IS1} in time.
The case of a S.C. in a thyristor of IS2 is different. In this case, a possible short circuit in the compensator output inverter is accompanied by a heavy short circuit current fed from the mains. This causes, in a very short time, the blowing of fuse f_{acP} which have a much lower rating than f_{IS1}. The duration of the voltage drop at the output is equal to the sum of the sag detection time of the static transfer switch [8] and of the fuse action time, and is thus similar to that of an ordinary transfer.

B. *UPQC*

An analysis of the action of protection devices in the entire compensator made it possible to construct the failure tree referring to the status of the voltage supplied by the UPQC, as shown in figure 5. The symbol V_2 denotes the RMS voltage furnished by the compensator at input 2 of the static transfer switch.

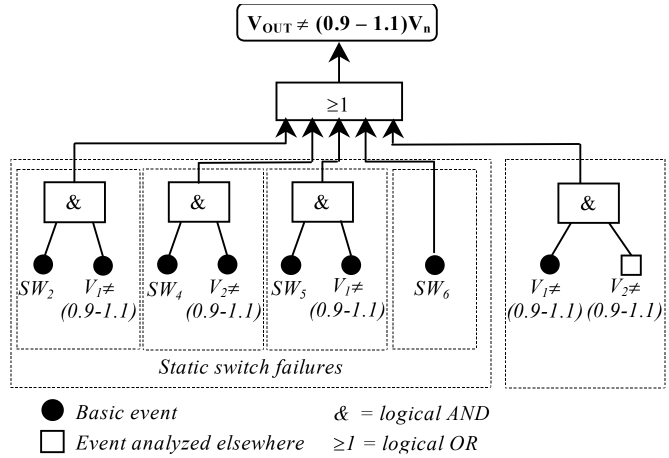

Fig. 4. Static transfer switch fault tree.

Table 3 shows the operational modes of the components making up the UPQC.

TABLE 3
OPERATIONAL MODES OF THE UPQC COMPONENTS

Section	*Operational modes*	*Typical cause*
Shunt unit	Sh_1: correct operation	
	Sh_2: short circuit	• power or firing circuit failure • output filter short circuit
	Sh_3: open circuit	• power or firing circuit failure
	Sh_4: control failure	• control logic failure
Series unit	Se_1: correct operation	
	Se_2: short circuit	• power or firing circuit failure • input filter short circuit • D.C. capacitor short circuit
	Se_3: open circuit	• power or firing circuit failure
	Se_4: control failure	• control logic failure
Input static switch	SWr_1: correct operation	
	Swr_2: short circuit	• power or firing circuit failure
	Swr_3: open circuit	• power or firing circuit failure
	SWr_4: control failure	• control logic failure
Energy storage unit	E_1: correct operation	
	E_2: short circuit	• cell short circuit
	E_3: high impedance	• positive grid corrosion [9] • dry-out • plate sulphation

The study examines the fault conditions which cause the output voltage V_2 to go outside the limits of tolerance, considering the storage system autonomy unlimited. This event is the *top event* of the UPQC fault tree, shown in fig. 5.
-Faults in the shunt unit inevitably lead to the *top event* because the voltage control function cannot be carried out.
-Faults in the series unit mean that the control function of the current drawn from the mains is no longer carried out. If the input static switch SW_r opens correctly, the device can function in islanding and the *top event* occurs only if there is a further fault in the storage unit or in the shunt converter. If the static switch fails to open, the situation depends on whether there is a S.C. or an O.C. in the series unit. In the first case, the shunt converter enters its limiting condition and the *top event*

takes place. In the second case, and if the voltage across the terminals of the injection transformer is lower than V_x^{max}, the current absorbed from the line disappears and the system functions in islanding.

-The failure to open on the part of the input static switch SW_r causes the *top event* if it happens together with a severe drop in voltage, which would necessitate the injection of a voltage higher than V_x^{max} by the injection transformer.

-Finally, the *top event* can occur due to a short-circuit across the storage system, which eliminates the D.C. voltage feeding the shunt unit and thus causing the loss of the voltage control function.

IV. Reliability performance analysis

A. Definition of the stochastic model

The calculation of the reliability of the load power supply is carried out using a stochastic model. This consists of the components of the compensation device, whose operational modes have been discussed above, and of a component which models the supply voltage furnished by the mains. The failure trees shown above require that this voltage should be classified according to three operational modes: between *0.9* and $1.1V_n$ (mode Ne_1), between *0.7* and $0.9V_n$ (mode Ne_2) and below $0.7V_n$ (mode Ne_3).

The overall system model employed has been constructed by making the following assumptions:

-stochastic independence between the system components. This is because the main cascading failures, due principally to the circulation of short circuit currents in components other than the damaged one, are avoided due to the presence of protection devices which quickly isolate the damaged component.

Common cause failures are very limited if the device is made to work under suitable environmental conditions, if adequate maintenance is provided and if necessary protection devices are installed against external disturbances (particularly surge arresters). Negative dependencies, which occur when the intervention of protection devices reduces the probability of faults in a section by cutting off the section's power supply, are on the other hand ignored;

-the repair of a component starts as soon as the fault has occurred, thanks to diagnostic signalling. The repair time includes the technician's travelling time, fault identification and repair and putting the component back into service.

The behaviour of a generic component *c* (inverter, static switch,..) is described by a stochastic process $\{X_c(t), t \in (0, \infty)\}$ in continuous time and with discrete states, where $X_c(t)$ indicates the state occupied by component *c* at time *t*. The process is stochastic both because the i^{th} generic state has a random duration, and because the successive state is chosen randomly from all the possible ones.

The transitions between the states can be described by the transition rates $a_{c,ij}$ between generic states *i* and *j*:

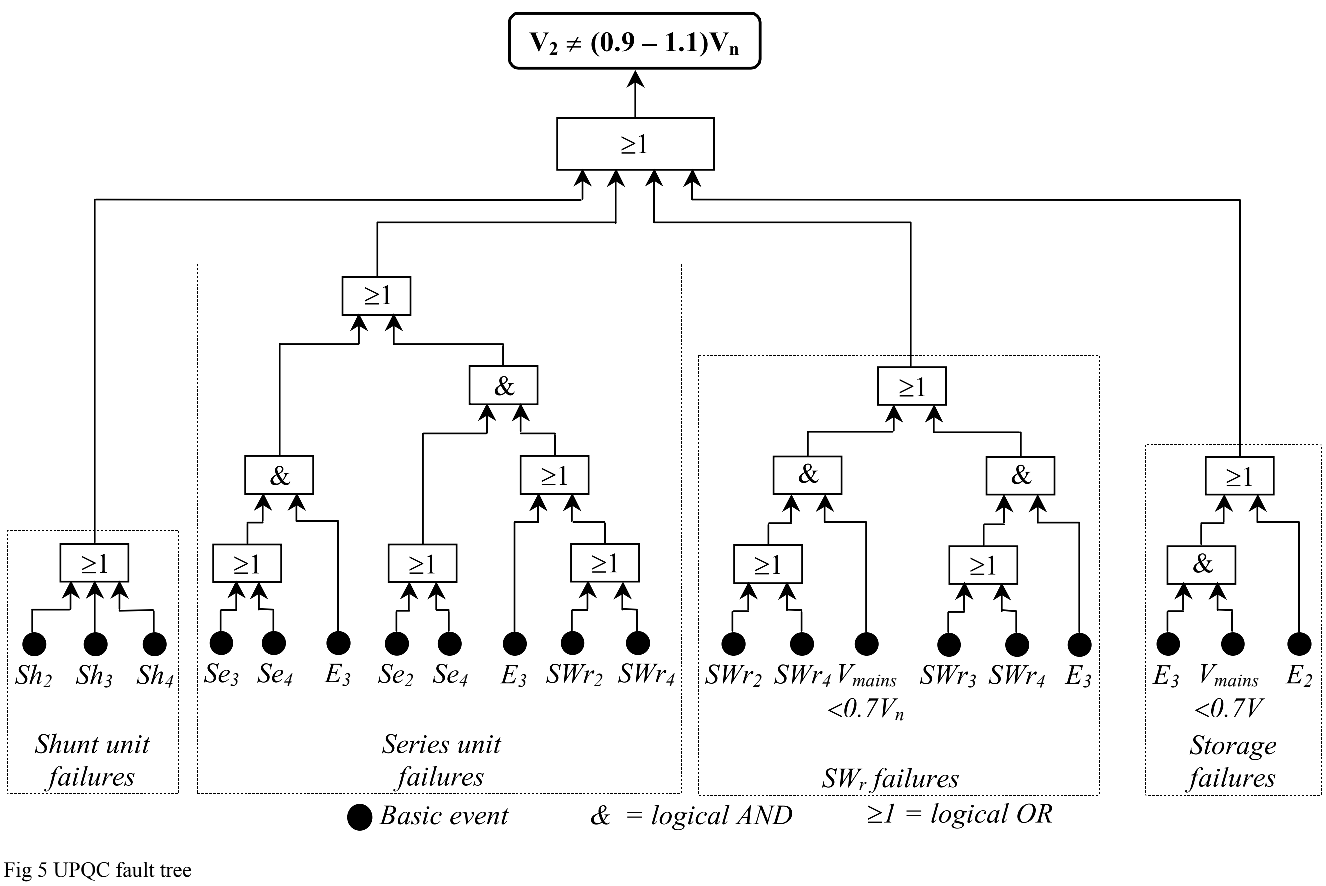

Fig 5 UPQC fault tree

$$a_{c,ij}(t)=\lim_{\Delta t\to 0}\frac{\Pr\{X_c(t+\Delta t)=j|X_c(t)=i\}}{\Delta t}$$

In order to evaluate the reliability parameters, it is sufficient to study the components under statistical steady-state conditions.

It is convenient to model the component using a Markov model, which describes processes possessing the following Markov property [10]: given that the component is in state i at time t ($X_c(t)=i$), the future states ($X_c(t+\nu)$) do not depend on the previous states ($X_c(u),\ u<t$). In this case and under stationary conditions, the rate of transition $a_{c,ij}(t)$ between state i and state j assumes a time-independent value indicated by $\lambda_{c,ij}$.

The duration of the generic state i is distributed exponentially, with the parameter $\lambda_{c,i}$ equal to:

$$\lambda_{c,i}=\sum_{\substack{j=1\\ j\neq i}}^{n_c}\lambda_{c,ij}$$

where n_c is the number of possible states for the component c.

The generic component c of the system can be studied using the Markov model shown in fig. 6, which possesses the following property: the state following that of correct operation is determined by the failure mode which occurs first, while the state following any failure mode is that of correct operation.

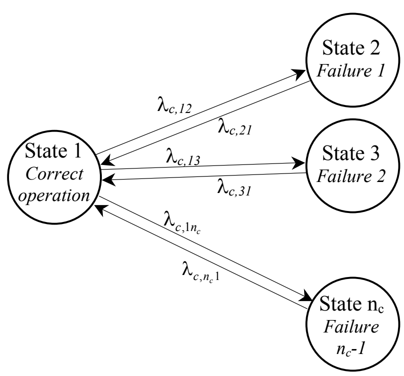

Fig. 6. Markov model for the generic component c.

The exponential probability distribution correctly models the time to failure during the useful life period. To represent the duration of repairs, it would be more useful to employ the Weibull or lognormal distribution [10]. However, thanks to the particular property of the components discussed above, the value of the parameters MTBF (Mean Time Between Failures) and MTTR (Mean Time To Restoration) is independent of the forms of probability distribution used for the duration of repairs, but depends only upon their mean value. It is hence permissible to assume all distributions to be exponential, considering their mathematical simplicity, as long as the mean value of the intervals is preserved.

The states S, which can be occupied by the overall system, can be obtained by combining the states of the components. Because of this, the system follows the stochastic process $\{S(t),\ t\in(0,\infty)\}$ in which the instants of transition correspond to the modification in a component state. The probability that two components should change their state simultaneously is zero, because of the assumption of independence between components and because the distributions of state durations are absolutely continuous.

The system, which is made up of Markov-type components in a stationary condition, is itself a stationary Markov process, with exponentially distributed durations of the states [11]. The rate of transition b_{hk} between states h and k of the system amounts to $a_{c,ij}$ if only the component c changes state by passing from i to j. If however more than one component changes its state, the rate becomes zero.

B. Calculation of reliability indexes

For each component c, it is possible to write and resolve analytically the state equations which describe the model of figure 6 [10]. We can thus obtain the probability $P_{c,m}$ ($1\leq m\leq n_c$) of occupying the state m as follows:

$$P_{c,1}=\Pr\{X_c(t)=1\}=\frac{1}{1+\sum_{j=2}^{n_c}\frac{\lambda_{c,1j}}{\lambda_{c,j1}}}$$

$$P_{c,2}=P_{c,1}\cdot\frac{\lambda_{c,12}}{\lambda_{c,21}}$$

. . . . .

$$P_{c,n_c}=P_{c,1}\cdot\frac{\lambda_{c,1n_c}}{\lambda_{c,n_c1}}$$

The probability of finding the system in the generic state $\bar{s}$, in which the N components occupy states $\bar{x}_1,\bar{x}_2,...,\bar{x}_N$, can be calculated by using the assumption of stochastic independence between the components, as follows:

$$P_{\bar{s}}=\Pr\{S(t)=\bar{s}\}=\Pr(X_1(t)=\bar{x}_1\cap...\cap X_N(t)=\bar{x}_N)=$$
$$=\prod_{z=1}^{N}\Pr\{X_z(t)=\bar{x}_z\}$$

In order to calculate the reliability indexes, it is necessary to define the subset B of states in which the output compensator voltage V_{OUT} is within the limits and the subset F of states in which it is out.

The steady-state availability of output compensator voltage A_{OUT} is the mean proportion of time when this voltage is within the limits and can be calculated as [10]:

$$A_{OUT}=\sum_{h\in B}\Pr\{S(t)=h\}$$

The mean time between failures of output compensator voltage ($MTBF_{OUT}$) is the mean time between consecutive transitions from the B subset into the F subset and can be computed as the reciprocal of the frequency of system failures ω_{OUT} [10]:

$$MTBF_{OUT}=\frac{1}{\omega_{OUT}}=\frac{1}{\sum_{h\in B}\left(P_h\cdot\sum_{k\in F}b_{hk}\right)}$$

The mean time to restoration of compensator output voltage ($MTTR_{OUT}$) is the expected value of the duration of sojourn in subset F and can be calculated as [10]:

$$MTTR_{OUT} = (1 - A_{OUT}) \cdot MTBF_{OUT}$$

Transition rates shown in table 4 have been used for calculating the values of the reliability indexes. These rates have been obtained from a study of the mains supply being carried out by the IEC and from experimental results on components of compensation devices obtained from tests carried out by a UPS manufacturer.

TABLE 4
TRANSITION RATES OF THE COMPONENTS OF THE SYSTEM

Component	*Failure rate (1/h)*	*Restoration rate (1/h)*
Input network	$\lambda_{Ne_1 \to Ne_2} = 6.772 \cdot 10^{-3}$ $\lambda_{Ne_1 \to Ne_3} = 5.016 \cdot 10^{-3}$	$\lambda_{Ne_2 \to Ne_1} = 16.2 \cdot 10^{3}$ $\lambda_{Ne_3 \to Ne_1} = 2.34 \cdot 10^{3}$
Static transfer switch	$\lambda_{SW_1 \to SW_2} = 0.2/(1250 \cdot 10^3)$ $\lambda_{SW_1 \to SW_3} = 0.2/(1250 \cdot 10^3)$ $\lambda_{SW_1 \to SW_4} = 0.8/(1250 \cdot 10^3)$ $\lambda_{SW_1 \to SW_5} = 0.8/(1250 \cdot 10^3)$ $\lambda_{SW_1 \to SW_6} = 1/(600 \cdot 10^3)$	$\lambda_{SW_2 \to SW_1} = 0.1$ $\lambda_{SW_3 \to SW_1} = 0.1$ $\lambda_{SW_4 \to SW_1} = 0.1$ $\lambda_{SW_5 \to SW_1} = 0.1$ $\lambda_{SW_6 \to SW_1} = 0.1$
Converters	$\lambda_{\substack{correct \to short \\ oper. \quad circuit}} = 0.2/(130 \cdot 10^3)$ $\lambda_{\substack{correct \to open \\ oper. \quad circuit}} = 0.8/(130 \cdot 10^3)$ $\lambda_{\substack{correct \to control \\ oper. \quad failure}} = 1/(600 \cdot 10^3)$	$\lambda_{\substack{short \to correct \\ circuit \quad operation}} = 0.1$ $\lambda_{\substack{open \to correct \\ circuit \quad operation}} = 0.1$ $\lambda_{\substack{control \to correct \\ failure \quad operation}} = 0.1$
Input static switch	$\lambda_{SWr_1 \to SWr_2} = 0.2/(1250 \cdot 10^3)$ $\lambda_{SWr_1 \to SWr_3} = 0.8/(1250 \cdot 10^3)$ $\lambda_{SWr_1 \to SWr_4} = 1/(600 \cdot 10^3)$	$\lambda_{SWr_2 \to SWr_1} = 0.1$ $\lambda_{SWr_3 \to SWr_1} = 0.1$ $\lambda_{SWr_4 \to SWr_1} = 0.1$
Energy storage unit	$\lambda_{E_1 \to E_2} = 0.5/(100 \cdot 10^3)$ $\lambda_{E_1 \to E_3} = 0.5/(100 \cdot 10^3)$	$\lambda_{E_2 \to E_1} = 0.1$ $\lambda_{E_3 \to E_1} = 0.1$

The results obtained are equal to $2.64 \cdot 10^5 h$ for $MTBF_{OUT}$ and to $4.39h$ for $MTTR_{OUT}$.

C. Effect of mechanical bypass

Often in compensation devices there is also a mechanical bypass which is closed quickly by the user during out-of-limit condition of voltage V_{OUT}: time taken by closing is negligible in comparison with the time to restoration of the compensator output voltage. So during restoration time the load is supplied directly by the mains and then duration of load voltage outage shortens and becomes unimportant in cost evaluation. On the other hand the frequency of load voltage failure increases because of mains voltage sags occurring during restoration time $MTTR_{OUT}$. As both states Ne_2 and Ne_3 cause load voltage failure, frequency increase $\omega_{MTTR_{OUT}}$ is equal to:

$$\omega_{MTTR_{OUT}} = (\lambda_{Ne_1 \to Ne_2} + \lambda_{Ne_1 \to Ne_3}) \cdot \frac{MTTR_{OUT}}{MTBF_{OUT}}$$

Mean time between two load voltage drops, named $MTBF_L$, is:

$$MTBF_L = \frac{1}{\omega_{OUT} + \omega_{MTTR_{OUT}}} =$$

$$= MTBF_{OUT} \cdot \left(\frac{1}{1 + (\lambda_{Ne_1 \to Ne_2} + \lambda_{Ne_1 \to Ne_3}) \cdot MTTR_{OUT}} \right)$$

This index is equal to $2.51 \cdot 10^5 h$: the increasing of the load voltage outage frequency is compensated for by the reduction of their mean duration.

V. CONCLUSIONS

At first a detailed study of the protection device has been carried out in order to analyse the UPQC behaviour during the faults of the components; then an evaluation from a reliability point of view has been done. This evaluation pointed out that the MTBF and MTTR of this compensator are not very different from the indexes of the usual double-conversion UPS.

The UPQC device seems to be promising because it is able to achieve performances close to the UPS ones, even if with higher efficiency and lower rating.

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