

# Development of Diagnostic Systems for the Fault Tolerant Operation of Micro-Grids.

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**Abstract**—The progressive penetration level of Distributed Generation (DG) is destined to cause deep changes in the existing distribution networks no longer considered as passive terminations of the whole electrical system. A possible solution is the realization of small networks, namely the Micro-Grids, reproducing in themselves the structure of the main production and distribution of the electrical energy system.

In order to gain an adequate reliability level of the micro-grids the individuation and the management of the faults with the goal of maintaining the micro-grid operation (fault tolerant operation) is quite important.

In the present paper after the introduction of the aims of several diagnostic systems, the main available diagnostic techniques are examined with particular references to those applied to the fault diagnosis of the electrical machines and finally the Authors also present an approach for the fault tolerant exercise of the micro-grid.

**Index Terms**—Micro-Grid, Fault Tolerance, Faults.

## I. INTRODUCTION

THE electrical distribution systems are actually, and will also be in the next future, the subject of deep changes, due to different factors. Among these those to be mentioned are essentially the liberalization of the electrical market, the most paid attention to an increased rational usage of the energy sources, the increased dissemination of automation and control for the management of the same sources and the increasing penetration of the Distributed Generation.

In particular, the forthcoming penetration of the Distributed Generation is destined to cause a deep change in the existing distribution networks. These networks, in fact, having actually a radial topology, are managed in a passive mode (for feeding the end users) but are also destined to reach an active role via implementation of the typical functions of load management, demand side management, generation curtailment.

A prospected solution to optimize the benefits and to minimize the inconveniences due to the Distributed Generation, is the realization of small networks (namely the micro-grids) reproducing in themselves the structure of the power generation and distribution system at a smaller scale. It is

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possible, for the isolation or the connection of the micro-grid to the main distribution network, to put the difference between autonomous (stand alone) and interconnected micro-grids; in this last case the micro-grid may be assimilated to active network cells constituted by a set of electrical loads and generators all connected to the main network through a single interfacing node.

The future revolutionary profiling scenarios do not consider the distribution system as a passive termination of the larger scale system, but as a network able to guarantee a "connectivity", i.e. the connection between producers and end users satisfying these last ones in terms of economy, availability affordability and reliability, with economical benefits coming out from the electrical market liberalization.

Also actually, the distribution systems are the subject of a very profound revision process with the goal of a deeper implementation of automation functions in order to increase the power quality and the services. The application to these system of an high level of information and communication technologies (ICT) will track the road map for the diffusion of the micro-grids that, still nowadays, are under investigation both on national (see SDNO - Smart Distribution Network Operation by ENEL Distribuzione) and international contest (see ADDRESS - Active Distribution networks with full integration of Demand and distributed energy RESourceS.)

All the hypothetical scenarios implies transformation and development processes that include, as put in evidence before, several issues concerning technical aspects ratios, interesting and fundamental studies fields and researches.

Whatever will be the future of the distribution systems, the maximum benefit from the distributed generation should be aimed thanks to the potential of the new information and telecommunication technologies. To get this target it will be necessary to overcome the manifold of problematics issued by the network management no longer characterized by unidirectional power flows, as for example, those regarding the non optimal development of lines and transformers, the complexity in the voltage regulation the unwanted islanded operations and the increased complication in the protection issues, the development of fault tolerant operation systems. [1], [2], [3]

In this paper the possibility of a fault tolerant operation of the micro-grid is investigated. In particular, after the introduction of the diagnostic systems for the micro-grids, the main diagnosis techniques for the fault detection in electrical machines actually available are examined and finally an approach for the fault tolerant operation development of the micro-grid is proposed.

Fault tolerant mode has a capital importance in the man-

agement policy of the micro-grid within a free market; in fact it implies consequences in terms of the continuity and power quality, with particular reference to the autonomous micro-grid, characterized by reliability levels smaller than those ones interconnected to the main distribution system.

## II. DIAGNOSIS SYSTEM, MONITORING AND FAULT INDEXES.

The ideal diagnosis system for the fault detection in an electrical system (electrical machines, power converters, electrical networks) has to be able to give a secure indication of anomaly not only of a fault presence but also of its typology and, eventually, to give also useful information on its location, entity and on its dynamical evolution during time.

Even if the modes of the fault appearance depends on the devices and on the operational environment, it is however possible to detect some effects or phenomena, common for each category of devices, in such a way to define the fault indexes. With the aim to realize an effective and economic diagnostic system all the fault and incipient fault indicators (or indexes) are to be monitored.

In order to individuate all those indexes, it is, first of all, necessary the verification through physical observations of the system states and of the quantities to be investigated undergoing through modification in the case of a fault or a pre-fault condition. After this, the presence of a deterministic or not bound between the monitored quantities and the fault condition is needed to extract a numerical model in order to make a comparison between the different states of the systems.

When the numerical model is really available all the comparison may be previously verified through simulation instruments.

As for the state of the art the effect of fault may be investigated in the frequency domain, it is necessary that each single signal acquired in the time domains if fast converted in the frequency domain with the Fourier Transform and for matter of best performances the FFT algorithm is very often used. From the frequency spectrum, in fact, it is sometimes possible to get the information about the hypothesized fault or pre-fault condition.

## III. FAULTS AND FAULT TOLERANT OPERATION OF THE MICRO-GRIDS

Due to the frequency and voltage variation in the distributed generation systems, the use of electronic power converters is mandatory to ensure the specifications that make the generated energy suitable to be injected into the network. In the field of distributed generation ancillary systems are also introduced. Among these the synchronization to the main network is one of the most important. This exigence is really of a capital importance for all the micro-grids for which the islanding operation is taken into account; in this case, in fact, a fault occurrence requires the disconnection from the main network in order to avoid the propagation of the fault to the public utilities, and the fast reconnection to this when the fault condition is eliminated.

The reliability of the modern power converters has limited the probability of faults occurrence, even more for those localized on the single power devices. Actually the most frequent faults are represented by short circuit and permanent switching off of a single device. Among these two faults the second has the highest frequency of appearance. On the other side, electronic power devices are protected by series connected fast fuses so that the short circuit condition rapidly evolves to the open line condition [6]. During the last years the construction of power converter is more often addressed to the usage of Power Electronics Building Block units (PEBB), i.e. circuit cells with various connected components and integrating protection inside conceived to realize the most diffused power convert topologies with a high degree of modularization [4], [5], [6]. For distribution systems it has been demonstrated that PEBBs can be used to develop diagnostic and protection tasks thanks to their integrated sensors with the advantage of the elimination of external sensors and external protection devices for the silicon components [5], [6].

Another interesting aspect issued to PEBBs is their ability to realize power conversion system that are also "fault tolerant" i.e. able to continue their operation after a fault occurrence with acceptable condition for the end user. This means in practice "with a low degree of power quality decrease". Furthermore there are some cases in which a significant decrease of power quality is only transient with a very small duration. Taking the intervention modes and the converter topologies into account, the fault tolerant converter may be divided into two big families:

- the redundant converters
- the non redundant converters.

The first ones are characterized by the presence of some devices not to be switched on during normal operation and used as back up units in the case of a fault occurrence with the loss of a converter leg. Figure 1 shows the case of a redundant fault tolerant converter. As a matter of fact this converter has an additional leg connected to each of the three phases of the load with a static device able to bidirectional conduction of current. The static version of the breaking device is preferred to the mechanical one because the switching on is to be made at load condition, with minor hazards and risks, and, in each case, it is faster than the mechanical breaker. The fault diagnosis and the fault tolerant operation of the redundant converter is articulated as follows:

- 1) the individuation of the faulted leg;
- 2) the disablement of the faulted leg drivers;
- 3) the gating of the TRIAC connected to the faulted leg;
- 4) the transfer of the switching control to the redundant devices.

The speed intervention is high enough to not determine a significant degradation of the power quality except for few commutation cycles or at least for a single cycle with a more sophisticated control. In an enhanced version of this converter more back up devices are present (making more legs available) and obviously a greater number of TRIACs for the connection to the load is needed. The fault tolerant condition is analogous except that for the absence of the third item.

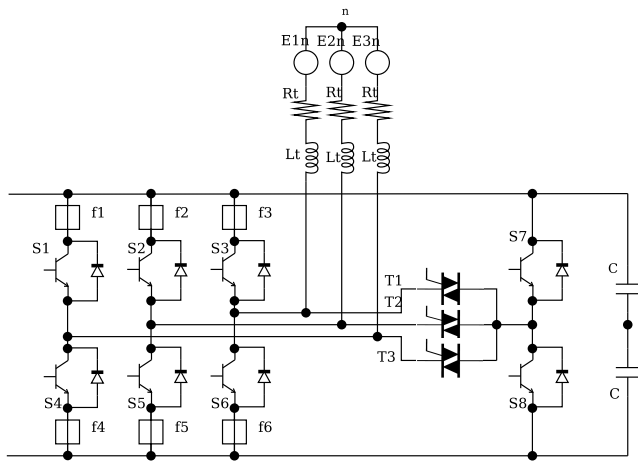


Figure 1. Topology of redundant fault tolerant converter

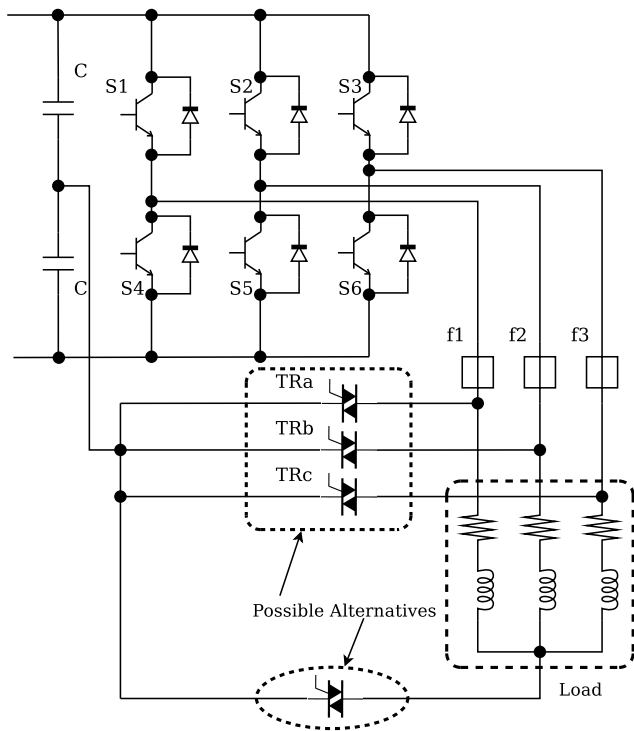


Figure 2. Topology of non redundant Fault tolerant converter

Figure 2 shows a non redundant fault tolerant converter: in this case the additional components are only the TRIACs connecting each phase of the load at the middle point of the DC Link. The switching on of such a TRIAC guarantees the enclosure of the current path both in the case of the fault of a silicon device and in the case of a phase interruption before the load. In the case of star connected loads with accessible neutral point only this point will be connected to the DC Link Middle through the TRIAC [7].

For these converters the fault tolerant operation is articulated as follows:

- 1) the individuation of the faulted leg;
- 2) the disabling of the drivers of the faulted leg;
- 3) the switching on of the TRIAC connected to the faulted leg;
- 4) the modification of the converter's control strategy (modification of the pulses sequence).

The fault on a single device reduces of two units the number of the realizable conduction states, but in spite of this it is still possible to follow the voltage reference with a suitable precision even if the normal linear range of the converters is reduced. In the case when the voltage asymmetry margins are narrow the usage of passive symmetrizing cells must be taken into account too.

Considering the non redundant converter topology it is interesting to note that as the faulted phase terminal is connected to the DC Link middle point the phase current is injected into the DC Link itself. This causes obviously a fluctuating difference in the capacitor voltages. However, fortunately this difference does not affect significantly the entire value of the DC Link voltage.

A symmetrical current system is gained using two different reference voltages for unfaulted legs, with a phase displacement of about 60 degrees. This displacement ensure the minimal asymmetry of the current system.

The voltage waveforms will be quite different from those with unfaulted converter condition and the faulted leg voltage exhibit the greatest difference. Furthermore the converter linear range is in each case restricted. Linear range is quite important in order to ensure the minimal asymmetry for the current system. An over-modulation running requires a modification of the displacement angle between the reference voltage in order to gain a sub optimal symmetry condition.

It is also clear that redundant converters show a wide degree of fault tolerance for a single device disruption. on the other hand the fault of more than one device is considered of a rare occurrence. However they are more expensive than non redundant converters just for the employment of a larger amount of devices and for the increased articulation and complexity of the control system.

#### IV. DIAGNOSIS OF THE ELECTRICAL AND MECHANICAL FAULTS ON ROTATING MACHINERY FOR THEIR FAULT TOLERANT OPERATION.

In the micro grid environment, besides the usage of fault tolerant converters there is the need to diagnose the generators developing a coordinate strategy for intervention in order to ensure the effective fault tolerance of the whole system as possible.

In fact, the modern electrical machines, power converter and the generation systems need a pointed-up identification of their operating condition with proper monitoring systems, sometimes also in spite of their high cost. In particular the recognition and the identification of the fault condition allow the operators to take specific procedures of planning only limited machine stops with the aim to allow them to continue their operation in some tolerable prefault conditions and in accordance within the planned intervention times.

In this way the times of service interruption are sensibly reduced and the planned maintaining and repairing may be conducted in a simpler way because the prefault condition is suddenly recognized avoiding its evolution to disruptive fault. In order to implement the correct operational strategies it is mandatory for the conversion system to include proper diagnostic services to individuate and localize the fault condition, insulating so only the malfunctioning apparatuses and devices.

In the following part of this section some of the most used diagnosis methods are recalled because they can be used within the philosophy of the fault tolerance in micro-grids and in coexistence of the fault tolerant converters, concurring to make them more efficient and to stimulate the penetration of distributed generation systems.

As known, the most part of faults in electrical machines, both in generating and motoring operation, is localized in the stator and rotor windings and on the bearings for the mechanical part. The electrical faults are essentially due to insulation faults and generally tends to evolve from the small short circuit within a small number of turns [9]. The bearings faults amounts typically the rate of 50% of all the faults in general and are due to mechanical degradation caused by the relative motion between the fixed and the moving parts of the machine [10].

In the technical literature a large number of diagnosis methods aimed to the individuation of the mentioned fault types were proposed. The best known are the following:

- 1) the method of partial discharge, suitable for machines with rating voltages higher than 4 kV;
- 2) the method based on the measurement of the axial flux component, suitable for low voltage machines;
- 3) the method based on the measurement of the inverse component sequence due to the presence of phase asymmetry under a fault condition;
- 4) the method based on the measurement of stator vibration useful in the case of both electrical and mechanical fault conditions;
- 5) the method based on the individuation of harmonic components on stator voltages and currents useful for the determination of both electrical and mechanical fault conditions.

The partial discharge method gives significant results if used in the case of electrical generators with rating voltage higher than 4 kV. Its natural application is in the field of high power Wind Generators.

The method based on the measurement of the axial flux component is instead more suitable for low voltage machines. Some researchers [9], [11], [12] have detected also the occurrence of short circuits between the winding turns with this method employing a “detecting coil” placed on the machine shaft. With four coils placed at proper distance on the four quadrants of machine shields the localization of the fault point is possible too. The method is suitable also in the presence of distorted voltages and current due to the usage of electronic power converters as for example voltage source inverters (VSI).

The method based on inverse sequence component use this one as fault index [13]. In fact, after a fault on the machine

windings, the different impedance between the machine phases causes an asymmetrical current system. The asymmetry degree of the stator voltages and currents may be employed for fault detection. The main drawback of this method consist in the fact that an eventual distorting action on currents, as for asymmetrical voltage, not due to a real fault condition, causes a false positivity in the diagnosis test. Taking these phenomena into account experimental results have shown that short circuit on single turns detection is possible.

The method based on the presence of stator vibrations is based on the fact that the fault condition determines a difference in the machine behavior respect to unfaulted conditions [14], [15], [16], [17]. In fact, the modified distribution of magnetic field in the air gap determines the manifestation of electromagnetic forces that cause some vibrations on the machine casing, just quite different from those present in an unfaulted machine. The measurements are made with the help of accelerometers or different motion sensors mounted on the machine casing, or on the shield when the axial vibrational components are of interest. The fault indexes in this case are given by the presence of such mechanical harmonic components at a given amplitude and frequency. The axial vibrating components allow also the determinations of short circuits between turns of the same phase and asymmetries in the feeding voltages that modify the distribution of the fields in the air gap. These modifications are also detectable in terms of the different noise coming out from the faulted machines.

The measurements of vibrating components, with particular reference to the radial ones, have been since many times one of the most suitable methods for the diagnosis of the bearing faults, because the experience accumulated in several years has allowed the individuation of many breakpoints (especially on the bearing balls and on the thrusts) due to a general increase in surface roughness. The first type of fault is recognized in virtue of the presence of harmonic frequencies multiple of the rotational pulsation, while the second type implies a modification of the spectrum shape. The vibrational analysis is also useful in the discovery of rotor eccentricities, partially responsible of bearing deterioration.

The MCSA method (Motor Current Signature Analysis) is based on the spectral analysis of the stator current is actually one of the most easy to use methods, especially for the availability of the employed sensor (e.g. Hall effect sensors), but sometimes it can also fail if the current presents strong harmonic contents. However the method can give effective indications of electrical faults both on the stator and on the rotor and also of mechanical faults even if with stronger limitation than in the previous method.

## V. ARCHITECTURE OF A DIAGNOSIS SYSTEM FOR A FAULT TOLERANT OPERATION

As shown in the previous sections, the identification of such a fault, requires the execution of several measurements, or better, a continuous monitoring of the interesting quantities. The values of such quantities are to be compared with the fault indexes whose determination starts from experimental investigation or by simulation results based on the mathematical model of the system under fault condition.

The fault detection through comparison between faulted and unfaulted conditions require a preliminary phase of intensive studies for the realization of comparison tables used in dependency of the considered micro-grid structure and on the interconnection of it with the main network. For this determination several “ad hoc” created simulation software are also available allowing the simulation of the behavior of each single device in order to establish the most suitable fault indexes [18].

The mentioned comparison tables can be easily implemented on digital architectures and "hardware in the loop" based on FPGA (Field Programmable Gate Arrays). The employment of such a system presents some advantages respect to the ASIC (Application Specific Integrated Circuits) Architecture [8].

Apart from the implementation issues, it must be observed that in some cases the fault tolerant operation is not possible at all, or become more complex as in the cases of multiple faults, or in some situations not recognized by the fault model. In particular, for certain permanent faults in the micro-grid the repercussion on the operation continuity are relevant till to require the disconnection of the micro-grid from the main public utility network (if this interconnection is effectively present).

In this section the Authors introduce a novel approach for the development of a diagnosis system for the fault tolerant operation of a micro-grid, followed by the eventual reconfiguration/modification or by the disconnection (in the proper cases) when the system recovery is not possible. The conception of the approach is schematized in the flow chart of figure 3.

As it can be inferred by this figure the fault or pre-fault condition is individuated through the comparison between the measurement result and the (pre)fault index. In particular, for the converter the following possibilities are contemplated:

- 1) in the case of a pre-fault the converter operate in fault tolerant mode, warning about its state;
- 2) if the fault contemplates the possibility of a reconfiguration of the converter it operates in fault tolerant mode;
- 3) if a fault with no possibility of reconfiguration is detected, the same converter is disconnected from the grid and turned off waiting for the repairing made easier by the knowledge of the fault type.

As for generator the following possibility are contemplated:

- 1) if a pre-fault condition, tolerable until the time of intervention on the system, is detected the generator continues with fault tolerant operation mode; the warning about the pre-fault condition allows, in each case, the setting up of the various procedures needed by the recovery without the disconnection of the generator from the main;
- 2) if a fault condition is revealed the generator have to be disconnected for the necessary recovery and repairing operations.

For all the other components of the network the following possibilities exist

- 1) if the fault has a transient nature, it can be recovered,

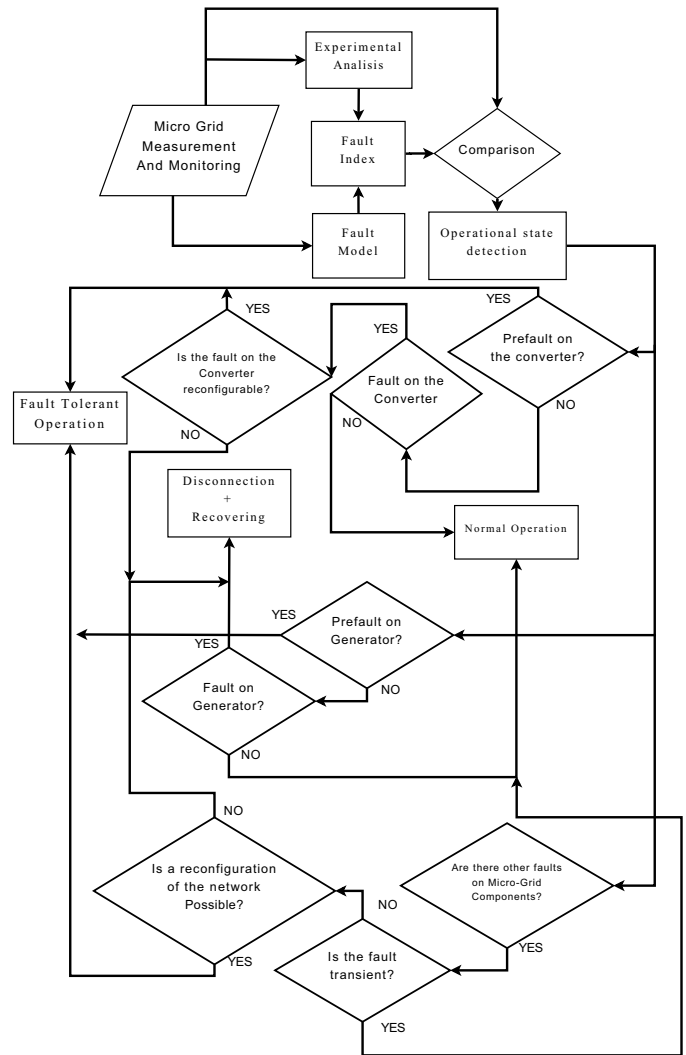


Figure 3. Flow chart of the proposed approach

simply by the process of disconnection and reconnection of the faulted branch or equipment. After this the micro-grid restarts its normal operation.

- 2) if the fault has a permanent nature and it results possible to reconfigure the micro-grid this reconfiguration is mandatory to reach the fault tolerant operation.
- 3) if the fault has a permanent nature and the micro-grid is not reconfigurable, it must be entirely disconnected by the main network (if previously connected), deactivated and recovered.

For all that concerns the faults on the distribution lines on distribution, it must be remarked that the entire distributed generation must be disconnected without any doubt with its interface devices in order to ensure the correctness of the procedure for fault elimination by disconnection and reconnection [3]

In fact in case of a poly-phase fault the presence of distributed generation, apart the passive loads, the devices for the selection of faulted branch and the eventual remote controlled devices could not sense correctly the fault condition. In the case of procedure implemented with device for the selection

of faulted branch it starts only if the fast reconnection of the breaker fails and the further actions are to be made in strong coordination with the line breaker operation through local voltage measurements really discriminant for the recognition of the fault condition. If the distributed generation would continue to work during the absence of network interconnection there would manifest strong anomalies caused by the fault enforcement by the generators.

In the case of procedure through STMT two cases are to be taken into account on the basis of the presence or not of the fault detection devices.

Without fault detection the same consideration already made for DSTG are still valid; when the fault detectors are present instead the distributed generation could activate detectors topologically put after the point of fault conduction to another failure consisting in the disconnection of the "sane" part of the network.

## VI. CONCLUSIONS

In this paper, after the presentation of the main aims of the diagnosis systems and of the fault tolerant converters, the main diagnosis techniques for the electrical machines were recalled and finally a novel approach for the fault tolerant operation of the entire micro-grid was presented and proposed.

The architecture proposed for such diagnosis systems is suitable for the use in conjunction with intelligent algorithms for fault detection and result to be simple to implement on low cost and user friendly hardware and, e.g. FPGAs. The FPGA modules, may be easily reprogrammed to adequate the control and diagnosis algorithms to the increased amount of knowledge and experimental data stored during time for the particular network under observation, considering above all its specific location and its capability in the production of electrical energy from renewable sources.

The development and the adoption of these systems is essential both for the optimal development of electrical power produced by renewable sources characterized by an high degree of randomness and for the assurance of high level of reliability and power quality, both of capital importance for all the end users.

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