ISLANDED OPERATION OF MV NETWORKS

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SUMMARY

Within the context of dispersed generation, this paper investigates the feasibility of operating MV feeders in an islanded mode when a long duration cut occurs on the HV side. In the case considered here, the power supply is then provided by a non-utility generation plant connected to the HV/MV substation.
Different aspects are investigated : steady-state voltage profile, voltage and frequency control, protection system and neutral grounding. Results of a case study performed on a real MV network are reported.

INTRODUCTION

Presently, EDF does not allow the islanded operation of medium voltage (MV) networks, where the power is supplied by a non-utility generation plant (NUG).

On the other hand, dispersed generation implying small power plants (a few MW) developed in the last decade on MV networks [1]. This tendency is due to different factors : special tariffs for renewable energy, cogeneration, facilities making use of waste products, cost reduction of materials and new production technologies, etc. Moreover, the application of European directive 91/96 should also contribute to this development.

This context then leads to the question : could MV feeders connected to a substation be operated in an islanded mode during a long duration power cut of the HV supply ?

Islanded network operation is already performed under special circumstances, for instance :

– exceptional operation of islanded HV networks following some specific incidents ;
– networks of industrial plants with generating sets ;
– insular networks or networks of remote isolated areas.

The point is to determine the conditions under which such an operating mode could take place and to assess the performance and quality deterioration that would result with respect to the normal interconnected operation (following the occurrence of a major incident, a supply of lower quality may be better than no supply at all !).

The paper focuses on the feeder reconnection after a loss of the HV supply (blackout on the MV network) and on the subsequent operation of the resulting islanded network. Islanded MV networks created by wanted or unwanted disconnections from the HV supply and the related problems that could arise (e.g. [2-3]) are not studied here.

Many aspects must be considered :

– maximum size of the MV network that can be supplied by the NUG,
– steady-state voltage profile,
– voltage and frequency variations when load is re-energized by the NUG (voltage and frequency control),
– protection system and neutral grounding,
– harmonics, fast voltage fluctuations, flicker, ...
– transmission of the 175 Hz tariff signal,
– real-time operation and remote control of the network,
– reconnection to the main system.

The first four points above are investigated in this case study. Simulations were conducted with the EUROSTAG software. The results are reported in the following sections.

SYSTEM DESCRIPTION

EDF MV networks generally consist of radial feeders which can be either entirely composed of underground cables, or be mixed and contain underground cables and overhead lines. In the HV/MV substation, the rated powers of the transformers can take fixed values ranging from 5 to 100 MVA.

The studied system is a rather typical one and is illustrated in Fig. 1. It consists of :

– a high voltage 63 kV busbar denoted HB,
– two 63kV/20kV transformers of 36 MVA rated apparent power, denoted T1 and T2,

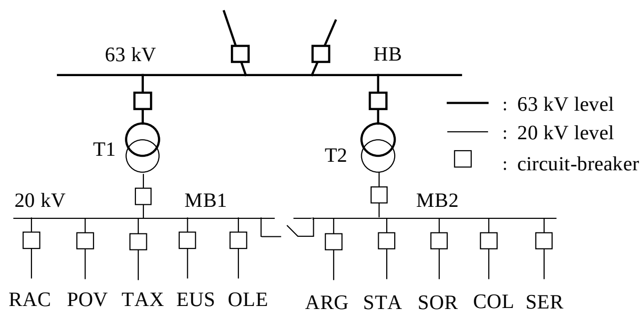

Figure 1 - The studied system in normal operating conditions

- two 20kV busbars denoted MB1 and MB2,
- 10 MV feeders connected to MB1 and MB2 (not represented in detail in Fig. 1).

In normal conditions, busbars MB1 and MB2 are operated separately, as well as the transformers T1 and T2. The two MV busbars could however be connected together for special operating purposes (maintenance, emergency conditions, occurrence of a fault on one of the transformers, etc.). In particular, for islanded operation, this feature will be used to supply the feeders connected to MB1 with power produced by a NUG connected to feeder “SER” (see Fig 1).

Feeder “SER”, connected to MB2, is composed of a 60 m long underground cable and is dedicated to the NUG. This latter consists of 4 diesel generators of 2 MVA, 1.6 MW, leading to a total apparent power Sg of 8 MVA and a total active power Pg of 6.4 MW (cos φ = 0.8, Qg = 4.8 MVar).

The other 9 feeders supply power to loads only and contain no generation plant. They are composed of several “load blocks”, i.e. they are divided in several sections containing a certain amount of loads, which are connected to each other through switching devices operated by remote control. The load power factor is equal to 0.93.

TABLE 1 - Characteristics of the “loads only” feeders

(1)	Cable % (2)	SL MVA (3)	PL % (4)	Nr Bl (5)	Max % (6)	Min % (7)	L km (8)	Ir0 A (9)	I2sc kA (10)
TAX	15	1.1	17	1	17	17	9	11	1.85
EUS	8	2.2	32	3	14	4.4	34	14	0.48
OLE	6	1.3	19	5	7	1.1	26	9	0.50
RAC	85	4.4	64	4	33	6.7	14	49	2.05
POV	84	4.2	61	7	34	0.3	20	68	1.83
ARG	100	4.5	65	7	22	1.5	12	37	2.27
STA	80	4.4	63	4	26	3.2	12	38	2.24
SOR	78	4.9	71	6	27	1.4	19	57	1.58
COL	100	3.3	48	3	28	3.8	12	43	2.47
Total	-	30.3	440	-	-	-	-	326	-

Characteristics of the 9 “loads only” feeders are given in Table 1, which is organized as follows :

- column 1 : identification of the feeder,
- column 2 : proportion of underground cables expressed as a percentage of the total length of the feeder (= sum of the lengths of all the branches in the feeder),
- columns 3 and 4 give the total load apparent power SL in MVA and the total load active power PL in per cent of the rated active power Pg of the NUG,
- columns 5, 6 and 7 give respectively, for each feeder, the number of load blocks and their minimum and maximum sizes in per cent of Pg,
- column 8 : length in km of the path connecting the MV busbar to the farthest point of the feeder; in the case studied, except for STA, it is also the “electrically” farthest point (i.e. with the path of largest impedance),
- column 9 : Ir0, value in A of the residual current Ir that would be measured by the feeder protection (i.e. on the feeder at the MV busbar) under rated voltage conditions when a single-phase fault is applied on a neighboring feeder (Ir is equal to 3 times the zero-sequence current). Ir0 is directly related to the total zero-sequence capacitance of the feeder (MV networks are grounded at only one point located on the incoming feeder).
- column 10 : value in kA of the phase current measured by the feeder protection when a two-phase short-circuit is applied at the electrically farthest point of the feeder, in normal conditions when the NUG is not connected.

The last line of the table gives for columns 3, 4 and 9 the total values over the nine feeders.

Maximum reconnected load

Only a part of the feeders could be supplied by the NUG in islanded operation; appropriate choices should therefore be made. In the simulations reported in the paper, the following configurations have been studied :

- CF1 : the NUG supplies entirely feeders TAX, EUS, OLE and a part of feeder COL,
- CF2 : entire feeder SOR and a part of feeder COL,
- CF3 : entire feeder POV and a part of feeder SOR.

The configurations take into account the size and the connection structure of the load blocks.

Modeling aspects

The network (the 10 feeders, busbars MB1 and MB2, etc.) is represented with three-phase models (positive, negative and zero sequences). The loads on the feeders are modeled as constant impedances in a 3-phase representation.

The 4 identical diesel generators of the NUG are connected to feeder SER through 4 identical LV/MV transformers. They have been aggregated into one equivalent diesel generator along with one equivalent LV/MV transformer. The different components were modeled according to the data and information received from the manufacturers :

- detailed 3-phase model of LV/MV transformer with Wye-Delta connection (Delta on the MV side) and 6.5% short-circuit impedance (in base 8 MVA),
- 3-phase model of a 3-winding synchronous machine,
- exciter and voltage regulator implementing a 2.5 % voltage droop (w.r.t. the reactive power of the generator) and an underfrequency module which reduces the voltage setpoint when the frequency decreases below an adjustable threshold (non-linear function in a given frequency range),
- speed regulator operating under isochronous mode,
- simplified model of the diesel motor; the received information did not permit to derive a complete and detailed model for this component.

The parameters of the regulator models were adjusted so that the simulations of the diesel generator could reproduce load connection curves obtained from the manufacturers.

STEADY-STATE VOLTAGE PROFILE

In normal interconnected operation, the tap-changers of the HV/MV transformers in the substation control the voltage of the MV busbars. It is generally maintained equal to a setpoint value between 20 kV and 21 kV. In the studied case, this value is 20.4 kV.

The voltage profile on each feeder is then determined by the voltage drops that the active and reactive power flows yield on the different sections. The network is designed to guarantee that the voltage remains inside the contractual range whatever the load level may be.

In the studied case, the NUG is almost directly connected to the MV busbar. In islanded operation, the voltage profile on the feeders will be almost unchanged provided that the NUG is able to control the voltage at the MV busbar and to maintain it equal to the setpoint value of the tap-changers. The steady-state voltage profile is thus a function of the active-reactive capability curve of the machine.

For a rated reactive power Qg of 4.8 Mvar and a 6.5 % short-circuit impedance of the transformer, the reactive power which can be supplied by the NUG on the MV side is of 4.28 MVar, corresponding to a tg φ of 0.67. At the maximum load level, the tg φ of the studied feeders at the MV busbar is much less. As a consequence, the number of feeders and load blocks that can be re-energized in islanded operation is mainly limited by the active power constraint.

Table 2 illustrates the above considerations for configuration CF1. It reports :

- the active power P, reactive power Q and corresponding tg φ at the machine LV and MV busses and on each feeder at the MV busbar,
- the voltage U at the machine LV and MV busses and on each feeder at the farthest point from the MV busbar.

As expected, the results obtained in the case study showed that a NUG (almost) directly connected to the MV busbar is able to keep the steady-state voltage profile unchanged.

TABLE 2 - Steady-state powers and voltages for CF1

	P (MW)	Q (MVar)	tg φ	U (kV)
Machine LV bus	6.45	2.41	0.37	0.42
Machine MV bus	6.4	1.9	0.30	20.43
TAX	1.1	0.3	0.27	20.37
EUS	2.1	0.7	0.33	19.66
OLE	1.2	0.4	0.33	20.09
COL (partially)	2.0	0.5	0.25	20.25

VOLTAGE AND FREQUENCY CONTROL

Voltage and frequency control during load variations mainly depends on the behavior and the parameter adjustment of the voltage and speed regulators of the NUG. The results of the simulations give an example of the performance of a NUG for the considered regulators.

19 different cases of load reconnection were studied, resulting from the combination of

- 4 initial loading levels of the NUG : initial active load of approximately 0 %, 50 %, 70 % and 90 % of Pg,
- 3 levels of reconnected load : approximately 10 %, 30% and 50 % of Pg,
- different types of feeders : with a large proportion of overhead lines, or of underground cables or mixed.

N.B. in the load levels, the size and connection structure of the load blocks of the feeders have been taken into account.

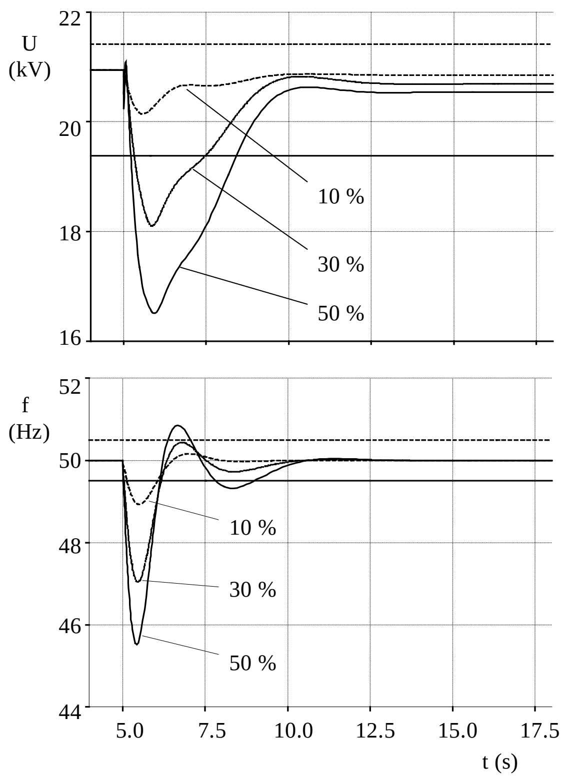

Figure 2 - Load reconnection : voltage and frequency curves

Fig. 2 gives the voltage and frequency curves for 3 cases. They provide a good illustration of the obtained results. Starting with a no load condition for the NUG, parts of feeders representing respectively 10 %, 30 % and 50 % of Pg are reconnected. The voltage setpoint at the NUG is such that, at full load (Pg), the MV side voltage of the transformer is approximately equal to 20.4 kV. In no load conditions, it is equal to 20.9 kV as shown in Fig. 2.

TABLE 3 - Load reconnection : voltage and frequency variations

Case (% Pg)	fmin (Hz)	fmax (Hz)	$t_{f1\%}$ (s)	Umin (kV)	Umax (kV)	$t_{U5\%}$ (s)
10 %	48.9	50.2	1.1	20.1	20.9	0.0
30 %	47.0	50.4	1.2	18.1	20.9	2.5
50 %	45.5	50.9	4.0	16.5	20.9	3.4

Table 3 gives the minimum and maximum values of the frequency and the voltage for the 3 cases, along with the times $t_{f1\%}$ and $t_{U5\%}$ after which the curves respectively stay inside the frequency range 50 ± 0.5 Hz and the voltage range 20.4 ± 1 kV. The range limits are drawn on Fig. 2.

The imposed voltage and frequency thresholds for the "disconnection protection" of the NUG are respectively (20.4 ± 3) kV (instantaneous for the maximum and with a time delay of 1s or 1.5s for the minimum), and either (50 ± 0.5) Hz or (47.5/51) Hz instantaneous [1]. Table 3 shows that, to meet these requirements, only a limited amount of load could be reconnected at the same time (less than 30 % of Pg). As a consequence, either choices have to be made between the load blocks or the thresholds of the NUG disconnection protection have to be changed (e.g. maximum load block for POV is 34 % of Pg - see Table 1).

Note that the above discussions apply for constant impedance loads (model used in the simulations). The study of frequency and voltage variations for the reconnection of motor loads has still to be done.

PROTECTION SYSTEM

Protection system against multiphase faults

In normal interconnected operation, the protection system against multiphase faults (2-phase or 3-phase) relies mainly on overcurrent protections with a constant time characteristic. They are implemented at the MV busbars on each outgoing feeder (10 feeders in the case study) and on the incoming feeders (from T1 and T2 to MB1 and MB2, see Fig. 1). The protections on the incoming feeders protect the MV busbars and serve as backup protections for the ones on the outgoing feeders.

When a multiphase fault occurs on a feeder, different scenarios have to be considered depending on the type of the fault and on the type of the feeder. The principal ones are briefly described below. The times given are indicative values and may vary or be adjusted in some cases.

For mixed feeders (composed of overhead lines and underground cables), a fast automatic reclosing cycle takes place. Let t0 be the time of the fault inception :

- at time t0+0.15s, the protection on the faulted feeder causes a 3-phase opening of the circuit breaker and hence the tripping of the whole feeder (provided that the measured phase current is greater than the threshold of the relay setting),
- at time t0+0.45s, the circuit breaker recloses ; then either the fault is cleared and the cycle stops, or
- at time t0+0.95s, the circuit breaker opens again and the protection system enters a slow automatic reclosing cycle (reclosing after 15 to 30 s and so on). This slow cycle has not been considered in the present study.

Note that the protection devices of the customers may also clear the fault when it occurs on their facilities. For instance, the protection system for customers directly connected to the MV voltage level is designed to clear a fault with a time delay of 0.2s after its inception. This feature must be taken into account in the above reclosing cycle, e.g. between times t0+0.15s and t0+0.45s or after time t0+0.45s.

For underground feeders, the protection system implies no automatic reclosing cycle. The 3-phase opening of the circuit breaker is definitive and, due to the implemented time delay of the protection, occurs approximately 0.5s after the fault inception. Then either the fault is cleared beforehand by the protection devices of a customer, e.g. at t0+0.2s, or the whole feeder is disconnected at t0+0.5s.

Regarding relay settings, the threshold of the protection on a outgoing feeder is set to a value larger than 1.3 Ip and smaller than 0.8 I2sc, where Ip is the maximum load current on the feeder, taking the backup configurations into account (e.g. the possible connections of load blocks of a feeder to another feeder) and I2sc is the phase current measured on the feeder at the MV busbar when a two-phase short-circuit is applied at the electrically farthest point of the considered feeder. Hence, any multiphase sound fault should be detected.

In islanded operation, two major points must be examined :

- is the short-circuit current provided by the NUG sufficiently high for the implemented protection system? Or has the protection system to be changed ?
- How is the dynamic behavior of the NUG affected by faults on the feeders ? For instance, may over-under frequency relays be triggered ?

To illustrate the first point, Table 4 gives the values of I2sc in islanded operation, at different times after the fault inception and for two cases : on feeder EUS in configuration CF1, and on feeder SOR in configuration CF2. The considered times take into account the above scenarios with and without automatic reclosing cycle, as well as a time delay related to the customer's protection system (0.2s - see above). Comparing with column 10 of Table 1, the values of I2sc decrease significantly.

TABLE 4 - I2sc in A for two cases in islanded operation

Case	I2sc (A)					
	without reclosing cycle			with reclosing cycle		
	t0	t0+0.2	t0+0.5	t0+0.45	t0+0.65	t0+0.95
CF1-EUS	367	292	275	385	302	277
CF2-SOR	748	479	435	802	522	446

For the studied MV network, the simulations show that the settings of the protection system have to be changed, e.g. the relay setting value for feeder SOR is 520 A and thus larger than I2sc for the considered time delays of the protections. Different possibilities may be considered :

- the thresholds of the relay settings may be reduced, provided that they stay above 1.3 Ip ;
- the protection time delay on the feeders may be suppressed leading to instantaneous disconnections ; the customer's protection devices will not be triggered anymore and the selectivity of the protection system will then be lost ;
- the clearing of mutltiphase faults may be performed by

the NUG protection on an instantaneous basis and the whole power supply will be lost in islanded operation.

Regarding the dynamic behavior, Fig. 3 gives the voltage and frequency curves obtained in 3 cases of sustained faults in the scenario with automatic reclosing cycle :

- case 1 : two-phase short-circuit applied at the farthest point of feeder EUS in configuration CF1;
- case 2 : 3-phase short-circuit applied at the same point,
- case 3 : 3-phase short-circuit applied close to the MV busbar on feeder SOR in configuration CF3.

The figure and the simulations of other cases show that very large voltage and frequency variations can be observed especially for faults close to the MV busbar. Extreme values of 35 Hz and 60 Hz have been obtained for the frequency and of 0 kV and 30 kV for the voltage. The large voltage values can be explained by the 3-phase opening of the feeder circuit breaker which corresponds to a load disconnection. The more the feeder is loaded the more the voltage is likely to increase. Of course, the above values greatly depend on the behavior of the NUG regulators and on the adjustment of their parameters. Other types of regulators could lead to rather different values.

Nevertheless, depending on the load of the feeder and on the type and location of the fault, the occurrence of multiphase faults and the subsequent voltage and frequency variations may trigger the disconnection protection of the NUG and lead to the loss of supply for all the feeders.

Protection system against single phase faults

Presently, most EDF MV networks are grounded by a limitation impedance at only one point located on the incoming feeder. This grounding is performed by means of a Neutral Point Coil (NPC) for underground networks and a Neutral Point Resistance (NPR) for mixed networks (composed of overhead and underground parts).

The protection system against single phase faults relies mainly on overcurrent protections with a constant time characteristic, which measure the residual current Ir on the feeders at the MV busbar. The threshold of the relay is set to a value small enough to detect the fault but larger than 1.2 Ir0 (see Table 1) to avoid the disconnection of a healthy feeder. Note that the triggering of the relay leads to a 3-phase opening of the circuit breaker.

As in the case of multiphase faults, both scenarios with or without automatic reclosing cycles may take place, depending on the types of the feeders. In some substations, the protection system may also rely on the use of a “shunt circuit breaker” (SCB), leading to the following scenario :

- at time t0+0.15s, the SCB closes and connects the faulted phase to ground at the MV busbar ; this often causes the fault to extinguish and thus avoids the tripping of the whole feeder,
- at time t0+0.4s, the SCB opens ; then, either the fault is cleared and no further action is taken, or after an adjustable time delay, the protection system enters one the two scenarios described previously (with or without automatic reclosing cycle).

Finally, overcurrent protections with inverse time characteristics are used to detect resistive faults. Such protections will not be discussed in the present paper.

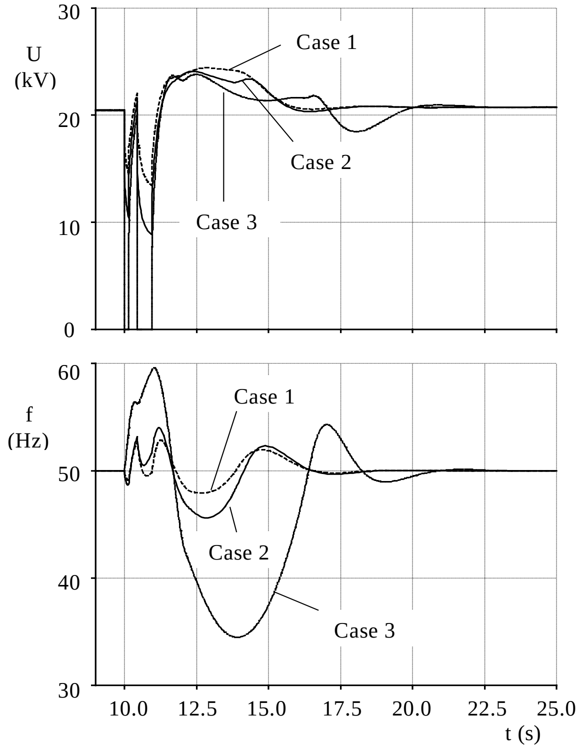

Figure 3 - Multiphase faults : voltage and frequency curves

In islanded mode, the neutral grounding on the incoming feeder is normally lost, leading to two possibilities:

- either operating the network with a isolated neutral,
- or grounding the network at a different point (only for islanded operation), e.g. on the MV side of the NUG transformer.

In the first case, some faults may remain undetected by the feeder protections. Indeed, the residual current Ir on the faulted feeder is equal to the sum of the capacitive currents of the healthy feeders. Its value may be less than the protection threshold. For instance, in configuration CF2, for a single phase fault at the farthest point of feeder SOR, the value of Ir on feeder SOR at the MV busbar is 35 A whereas the value of the threshold is at least 68 A. In such a case, the fault can only be cleared by tripping the NUG.

Moreover, network with ungrounded neutral can only be operated when the sum of the Ir0 values for the network is smaller than 30 A [4], otherwise overvoltage phenomena may arise for restriking faults.

The second solution will then be preferred. In the case study, the following results are observed when, for example, the neutral is grounded by a 40 Ω NPR on the MV side of the NUG transformer.

The residual currents Ir measured by the feeder protections for single phase faults are close to those measured when the MV network is supplied by the HV side through the HV/MV transformer. Thus, the protection system is still appropriate. Fig. 4 gives the values of Ir on the feeders in configuration CF2 for a fault at the farthest point of SOR; the fault is cleared by the closing of the SCB.

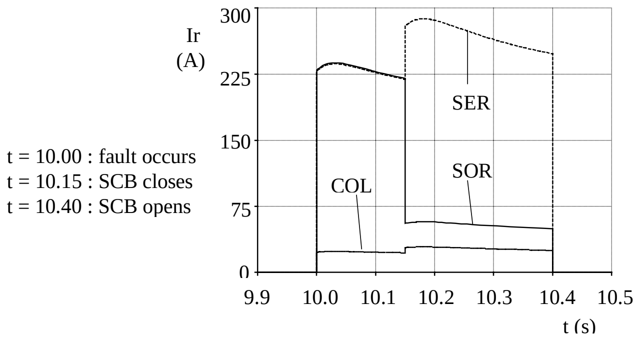

Figure 4 - CF2 : residual currents for a fault on SOR

Regarding the NUG dynamic behavior, the frequency decreases after the fault inception, due to the active power dissipated in the NPR (about 3 MW). Moreover, for heavily loaded feeders, the successive reclosings resulting from the automatic reclosing cycle lead to large frequency and voltage variations. These variations may cause the tripping of the NUG. Note that each opening (respectively closing) of a feeder circuit breaker leads to a 3-phase disconnection (respectively reconnection) of the whole feeder and thus of the corresponding load. Fig. 5 illustrates the above considerations for configuration CF2 in 2 cases :

- a fault cleared by the closing of the SCB ,
- a permanent fault with automatic reclosing cycle after the opening of the SCB. The slow automatic reclosing cycle is not shown ; it begins 15s to 30s after the fault inception and corresponds to successive load reconnection and disconnection

Note that, once again, the dynamic behavior of the NUG in terms of voltage and frequency very much depends on the regulators and on the adjustment of their parameters.

CONCLUSIONS

The islanded operation of MV networks has been investigated in the case where a non-utility generation plant (NUG) is almost directly connected to the MV busbar of the HV/MV substation. Different aspects have been considered and the following conclusions can be derived.

In islanded operation, the NUG should be able to maintain the voltage profile, provided that the machine active power capability is not exceeded.

Depending on the MV network (size of the load blocks, protection settings, types of the feeders, etc.), a careful analysis of the protection system has to be done. Relay settings may have to be changed for the feeder protections and for the NUG disconnection protection.

Anyhow, for dynamic aspects as well as for steady-state ones, choices between the load blocks to re-energize have to be made.

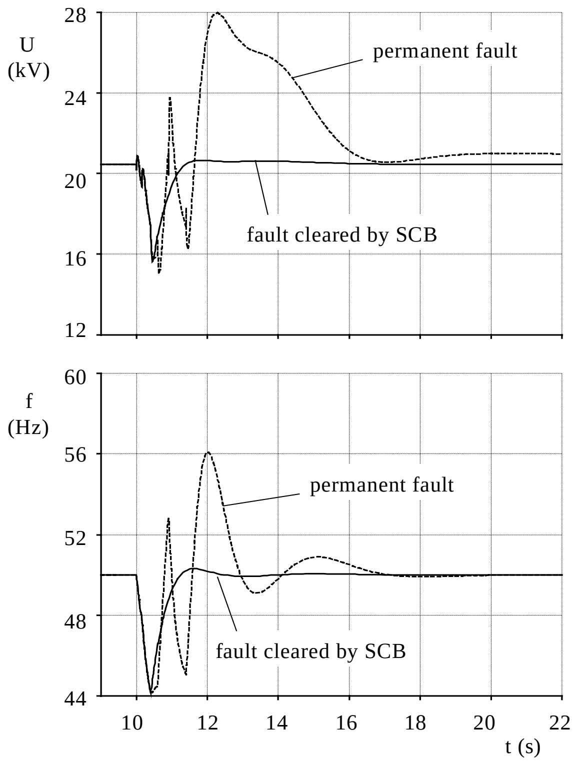

Figure 5 - Single phase faults : voltage and frequency curves

This paper results from a first stage study. Further investigations should be performed, concerning for instance the influence of the type of load (e.g. motors) and of the voltage and speed regulators, other connection configurations for the NUG, the problems related to the presence of several NUGs on a MV network. In particular, the impact of islanded operation on the quality of supply should be assessed from the customers' point of view.

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