Loss Of Mains Protection Using Enhanced Combinations Of Protection Criteria

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I. Abstract

Due to the ecopolitical trend for better utilization of primary energy and process heat, the mains parallel operation of smaller and medium sized power generating systems gains more and more in importance. In some cases, though the mains parallel operation of several generators can cause some problems and especially when failures occur in the public grid, the operator has normally to ensure that the power generating system is decoupled automatically from the faulty remaining grid.
This paper is about enhanced criteria which allow to identify mains failure conditions which must lead to disconnection of embedded generators. The main focus lies on the measuring procedures of vector surge detection and evaluation of the rate of change of frequency (df/dt or ROCOF).
In particular this paper shows that the behaviour of those quantities relevant for protection measures can be estimated in advance by means of calculation.

II. Introduction

The following introduction describes basically the principles of mains decoupling and the effects occuring in case.

A. Mains decoupling reasons

In this paragraph a number of system faults and switching actions are given which must result in decoupling of the private supply system to avoid the risk of endangering the own system or the own generator. Decoupling means opening of the closed inter-tie C.B. where the private power system and public grid are connected. The mains can be decoupled either

- without preceding voltage changes (e.g. manual switching off, overload tripping) o r
- after a voltage change (short circuit with or without automatic reclosing, conductor disruption)
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B. Mains disconnection without preceding voltage change

A synchronous generator, which had exchanged energy with the Electrical Supply Authority via a connection line, changes to isolated operation after a CB has opened (see Fig. II-1). In such cases it is possible that a residual load remains at the generator side and this load the generator carries on supplying.

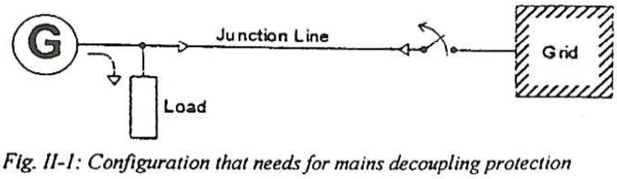

Fig. II-1: Configuration that needs for mains decoupling protection

Conditional on the active and reactive power component in the isolated system, the following dynamic behavieur can be predicted after first approximation:

- When the active power load increases during forming of the isolated system, the generator speed decreases and so that of the isolated system.
- When the reactive power load increases during forming of the isolated system, the generator terminal voltage decreases.
- When loading of the generator increases through active power <u>and</u> reactive power during forming of the isolated system, the voltage vector of the generator and by this the residual grid drops back immediately within a few cycles.
- Even after the "jump" the voltage vector keeps changing its position according to this frequency behaviour: If the load is further increased, the vector drops back even further and advances more and more at deloading.

Those following rules of thumb are valid for the transient time range 10-300 ms after the mains failure at conventional systems. Only after this time the speed / frequency or voltage of the driving genset and the generator are influenced by their regulators. Special attention has to be paid to very fast control systems like the SEG Concycle®. Its regulators are so fast that they can compensate transient changings within a time periode of some milliseconds. For such systems special criterias are under development.

N o t e:

- As to the first moments of the explained transients, the afore said normally applies to asynchronous generators and big asynchronous motors as well because their "excitation energy" derives at first from the rotor current (for slip reasons).
- For a synchronous motor generally the same applies as to a synchronous generators, the significant difference is that the motor is not driven but just can use its flywheel for feeding energy into the mains. The speed decreases instantly; the voltage behaviour is conditional on the excitation status defined before mains decoupling.
- In case the energy of a private power generating system is fed into the mains via an inverter, the active power and reactive power output drops very quickly to zero. Only for a short time after mains decoupling the voltage of the isolated system is backed slightly by asynchronous motors connected to the grid.

C. Mains disconnection after preceding voltage change

Voltage changes can have different reasons (e.g. short circuit with or without automatic reclosing).

Since it is intended that the mains is decoupled directly after a short circuit -and this applies especially to systems where the connection lines are provided with auto reclosing facilities- the mains transient for the generator and the driving genset is a short circuit with following quick clearance (see Fig. II-2).

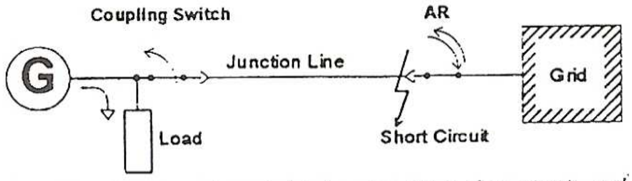

Fig. II-2: Forming of an isolated system by a short circuit and automatic reclosing

During the first phase of the mains failure the voltage at the generator terminals collapses according to the impedance ratio. Due to the high-inductive short circuit angle of the connection line, the voltage at the generator terminals become highly inductive as well. This now results in advancing of the (reduced) voltage vector. Because the active power at the generator decreases at the same time, the speed increases (slightly) and the voltage vector advances even further.

By opening the circuit breaker the mains failure enters into the second phase where the faulty section of the line is switched off from the generator and from the remaining load. Only now the voltage recovers and on the whole the dynamic force is similar to that described before, conditional on the active and reactive power component in the isolated system. Also when the mains is as quickly decoupled as in this case, it can be assumed that the dynamic of mains decoupling progresses without influence until speed / frequency or voltage are controlled by the regulators.

III. Decoupling Criteria

Conventional decoupling criteria are.:

- Voltage (U<, U>)
- Voltage unbalance
- Reverse power (P_{INV})
- Frequency (f< , f>)
- Load change (ΔP)
- Overcurrent and undervoltage (I>& U<)
- Directional overcurrent ($I>_{\rightarrow}$ & U<)
- Underfrequency and undervoltage (f< & U<)

Some of this criterias are disadvantageous because they are only suitable for some grid configurations, or they have to be delayed to prevent false tripping. So the know how is to find the suitable combination of criteria for a special configuration.

A. Rate of change of frequency (df / dt)

When measuring the rate of change of frequency, it is not the momentary frequency existing at that moment what is measured, but the rate at which the frequency changes (df/dt). By this the tendency can be detected before the frequency has changed to such a degree that it is beyond an absolute limit.

Additional to the actual measured frequency value, a df/dt relay has to be used so that the previous values can be considered and by this the tendency of frequency change can be analysed.

There are two different requirements on a frequency trend analysis:

- Fast tripping
- Security against nuicance trippings

To achieve more security against nuicance trippings, the frequency has to be observed for some time (several measuring intervals) by which the tripping time is delayed. Switching operations in the mains, however, may displace some zero passages and so fake two contrary frequency changes with the effect that for instance, the first cycle is measured too short and the following one measured too long; Increasing frequency followed by a decreasing one is detected by relays. As precaution against trippings, the relay therefore has to evaluate the direction of the frequency change and its continuity. This requirement is met by digital protection relays and extensive algorithms are used to eliminate the noise of measuring faults in frequency measuring values. A change of, for instance, 1 Hz/s causes the cycle duration to alter just about 4 µs per cycle. As comparison : The normal cycle duration at 50 Hz is 20 ms. This difference requires a high accuracy of the relevant relay so that frequency changes can be recognized precise enough.

As to the measuring side of this method these were the essential facts.

A different problem is how to define the correct tripping value. When considering the quickest possible tripping time at maximal security against trip conditions, the architecture of the mains has to be taken into due account. Not only the power supplier but the consumers as well have an influence on the extent of frequency changes. Influencing parameters are:

- Kind of drive (inertia)
- Kind of consumers (own ones and those of the public grid)
- Kind of switching operations

In the following Fig. III-1 a typical frequency behaviour after shut-down of the mains is shown. Prior to shut-down the isolated system was supplied by the public grid partially. At first the generator speed decreases constantly because the generator has additionally to supply the mains consumers. Later on the engine governor intervenes and tries to correct the speed dip.

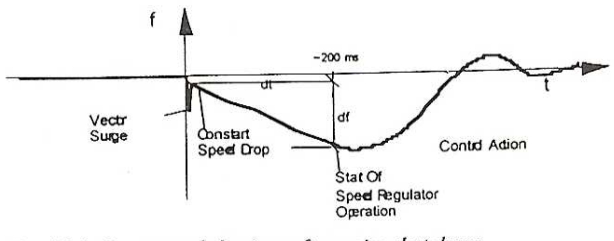

Fig. III-1: Frequency behaviour after mains shut down

Two measuring methods we have realized in our relays will be explained more detailed in chapter 4. These are:

- df/dt mean value measuring (two-point method)
- df/dt "quasi-instantaneous-value" measuring

B. Vector surge

This principle can be explained on the basis of a normal type synchronous generator consisting of internal voltage U_P and generator main reactance X_G ; Z_L stands for connected consumers, Fig. III.2. By CB S the mains failure is simulated at t = 0.

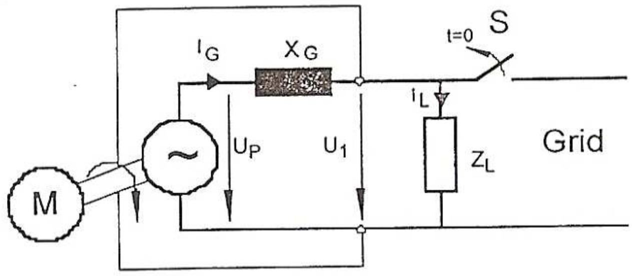

Fig. III-2: Simulation circuit diagram

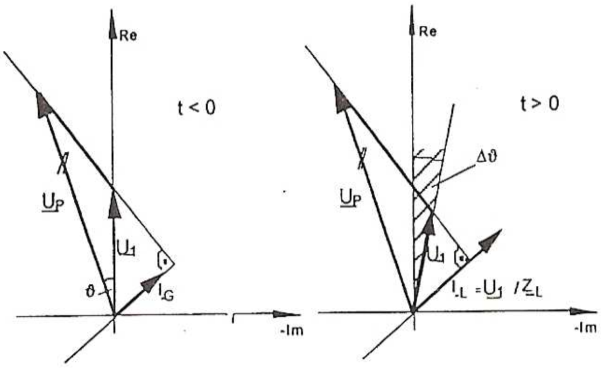

Fig. III-3: Phasor diagrams

The rotor displacement angle υ is the angle between internal voltage and generator terminal voltage U_1

In case of power output at the generator terminals, an angle difference between terminal voltage U_1 and internal voltage U_P develops (Fig. III-3: t<0). due to reactance X_G. This angle is called rotor displacement angle.

Prior to decoupling consumer Z_L is partly fed by the mains and partly by the own generator.

In the following example it is assumed that added to load Z_L power is not only being imported from the generator but from the mains as well. If the mains supply is interrupted (t>0), the additional power suddenly imported from the generator is equivalent to the quantity imported from the mains previously. Because of its inertia, the rotor will not abruptly change the speed. Therefore at first the internal voltage does not change. The rotor displacement angle is changed by current change $I_G \rightarrow I_L$ and so is the phase angle of the terminal voltage which is now not defined by the mains any longer but by the load angle of the isolated system.

The change of angle happens very quickly and other effects of this load change (speed drop) reach relative to this a measurable quantity only at a later time.

As it can be seen from Fig. IIII-4, the generator terminal voltage U_1 jumps to a different instantaneous value.

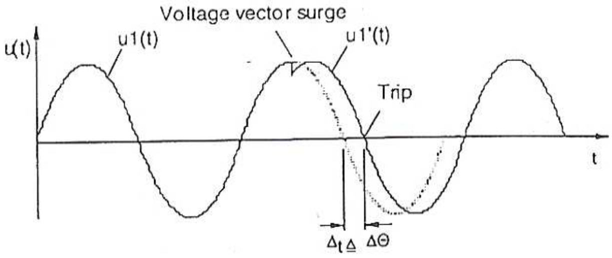

Fig. IIII-4: Oscillogram of the generator terminal voltage at the instant the mains is switched off

Through this the next and also the following voltage zero passages occur at a different time than expected.

Consequently measuring the time between the voltage zero passages is the most reliable way for protection devices to detect an angle change. To define the moment this will happen, the relay needs an internal reference. Slower processes, such as changes of frequency and voltage must not cause unintended trippings. Hence it is essential that the reference is always adjusted to the actual mains frequency. A measured time difference Δt is proportional to a angle change $\Delta\vartheta$ occured. The relay trips if the set value is exceeded.

The vector surge supervision is a principle very suitable for quick mains decoupling. By using this method tripping times of about 20 ms (without CB operating time) are possible.

IV. Calculation Methods and Measuring Results

A. Preparing the mains model (Reduction to the relevant components)

By the following mains components the dynamic behaviour of mains decoupling is defined:

- Generator and driving genset
- Mains load
- Connection line (in case the dynamic behaviour is influenced by short circuit)

B. Generator simulation circuit diagram and driving genset

Basis for analysing the dynamic behaviour at the generator is the well-known plain simulation circuit diagram, consisting of an internal EMF U_P (electromotive force) and an internal reactance X_G (see fig. III-2).

In the following dynamic processes are mainly explained on the basis of phasor representations. This is easy from the technical point of view and familiar to the application engineer. As experiences in practice and specific measurements have shown this absolutely meets the requirements for rating and adjustment of protection systems.

For analysing the dynamic behaviour with regard to protection measures it is advantageous to divide the time range of interest into "time windows"

- For the first 20 - 40 ms, the subtransient EMF E" can be entered in the first time window as internal voltage EMF and the subtransient generator reactance X" as internal resistance (duration of subtransient processes)
- For a time of about 40 ms until at least 400 ms, the transient EMF E' can analogously be entered in the second time window as internal voltage and the tran-

sient generator reactance X' as internal resistance (duration of transient processes)

Many motors in the island section increase the actual existing generator capacity during the first moments after mains disconnection. Because of their flywheel these motors operate as generators for a short while.

At the same time these motors reduce the relevant reactance for calculation of the dynamic behaviour during this time. They have to be considered parallel to the generator reactance. The only parameter needed for calculations is the inertia constant of the complete genset. Regulator originated effects show only after a later time and so they have not to be taken into consideration separately.

C. Simulation circuit diagram of mains load

After a mains failure has occured, the generator terminal voltage changes with the effect that the active power imported by several consumers changes as well. This shows that the dynamic description of the isolated system load as MW or MVAr is insufficient. It is more correct to regard the mains load as parallel connection of an ohmic and an inductive resistance.

D. Connection line

All lines connected between the location of the power station and the interconnection point of the public grid should be combined as one connection line. The series connection for the ohmic and inductive resistance portion of the line impedance has to be used here.

V. Calculation

A. Theory

Fig. V-1 shows the location of the main decoupling relay. The following equations explain the change of voltage, voltage phasor and frequency.

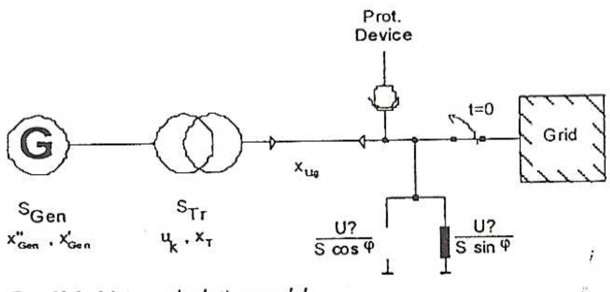

Fig. V-1: Mains calculation model

Formulas are quoted from [1], and for the time window of interest for protection purposes (transient time constant 40 ms - 400 ms), the transient generator reactance X' should be entered as the relevant quantity. For the subtransient range X" is to be used.

$$\frac{\underline{U}_{Ph+0}}{\underline{U}_{Ph-0}} = \frac{1+x'\cdot s_{-0}(\sin\varphi_{-0}+j\cdot\cos\varphi_{-0})}{1+x'\cdot s_{+0}(\sin\varphi_{+0}+j\cdot\cos\varphi_{+0})} \quad (1)$$

$$\frac{|\underline{U}_{Ph+0}|}{|\underline{U}_{Ph-0}|} = \left[\frac{(1+x'\cdot s_{-0}\cdot\sin\varphi_{-0})\cdot+(x'\cdot s_{-0}\cdot\cos\varphi_{-0})\cdot}{(1+x'\cdot s_{+0}\cdot\sin\varphi_{+0})\cdot+(x'\cdot s_{+0}\cdot\cos\varphi_{+0})\cdot}\right]^{\frac{1}{2}} \quad (2)$$

$$\delta_{\varphi'} = +\arctan\left[\frac{x'\cdot s_{-0}\cdot\cos\varphi_{-0}}{1+x'\cdot s_{-0}\cdot\sin\varphi_{-0}}\right] - \arctan\left[\frac{x'\cdot s_{+0}\cdot\cos\varphi_{+0}}{1+x'\cdot s_{+0}\cdot\sin\varphi_{+0}}\right] \quad (3)$$

with

$\underline{U}_{Ph-0}$, $\underline{U}_{Ph+0}$	mains voltage before or after mains disconnection
$\delta_{\varphi'}$	vector surge of isolated system voltage at time t' (t' = transient time constant of the generator)
x' (p.u.)	transient total reactance (relevant reactance) of the voltage source up to the location of the protection relay, consisting of the transient generator reactance, reactance of the step-up transformer and the line between generator and measuring point ($x' = x'_{Gen} + u_{k,Tr} + x$ line)
s_{-0}, s_{+0}	generator load before mains decoupling and remaining apparent load of the isolated system after mains decoupling, referring to the rated voltage
φ_{-0}, φ_{+0}	load angle of generator load before and of apparent load of the isolated system after mains decoupling

After the mains decoupling progressive twisting of the voltage phasor happens. According to the theory and the signs from [1] , here the phase angle φ(t) of the voltage vector $\underline{U}$(t) results from :

$$\frac{df}{dt} = \frac{f_N}{2\cdot H}\cdot\frac{P_{erz}-P_{neu}}{S_N} \quad (4)$$

with $P_{new}=P_N \cdot (U/U_N)$_

$$f(t) = f_N + \frac{df}{dt}\cdot t \quad (5)$$

$$\frac{d\varphi(t)}{dt} = 2\cdot\pi\cdot f(t) \quad (6)$$

with:

f_N	rated mains frequency
S_N	rated apparent load of the generator
P_{erz}	load of the driving genset during disconnection of the mains
H	inertia constant of the complete machine set
P_{new}	load after mains disconnection
P_N	load at nominal voltage
U	voltage in the isolated system
U_N	nominal voltage of the grid

Typical values of the inertia constant H for turbo sets are 2..10s at 3000 RPM and for salient machines 1.5 ... 6s. (More details in [1] and [2]).

B. Model calculation

For that purpose diagrams were prepared containing the expected change in voltage (equation [1]) and in angle position (equation [3]) as well as the arising frequency gradient (equation [4]) immediately after mains decoupling. With these results the load situation after decoupling is taken into consideration.

System data:

The relevant reactances and the inertia constant can be calculated by using the following equations. The inertia constant is only necessary for defining the frequency gradient.

Fig. V.2 show in a diagram typical result for given configurations.

Total reactance:

$$x_{ges}[p.u.] = \frac{S_{nG}}{U^2}\left[x'_d[p.u.]\cdot\frac{U^2}{S_{nG}} + X_T + X_L\right] \quad (7)$$

x_{ges}	total reactance in p.u.
S_{nG}	Generator apparent load
U	Rated voltage
x'_d	transient generator reactance (if available)
X_T	Transformer reactance (if available) [Ω]
X_L	Line reactance (if available) [Ω]

Inertia constant:

$$H = \tfrac{1}{2}\cdot T_A$$

$$T_A = 2{,}74\cdot\frac{GD^2}{S_n}\left(\frac{n_n}{1000}\right)^2 \quad (8)$$

$$GD^2 = 4\cdot J$$

H	inertia constant [s]
T_A	start-up time constant [s]
GD^2	inertia [tm^2]
S_n	rated load [MVA]
n_n	rated speed [min^{-1}]
J	inertia constant [kgm^2]

Load	S	Cos φ
Before	100%	0.9
After-wards S_i	0...400 %	0.8...1

Parameter	
x_{ges} [p.u.]	0,3
H	3 s
f_N	50 Hz

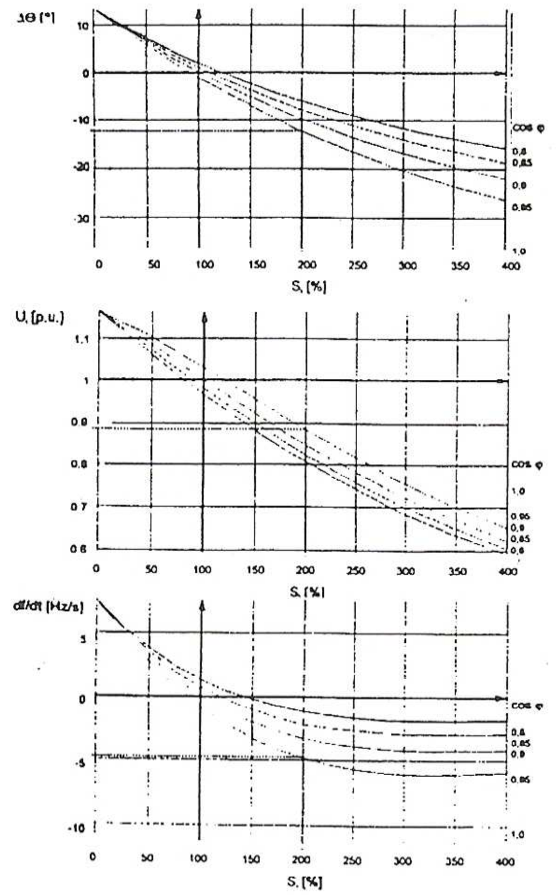

Fig. V-2: Change of angle, voltage and frequency gradient expected for a specific grid configuration

VI. Summary

For captive power generating systems operating parallel with the mains it is very important that in case of mains failures they are quickly decoupled from the public grid [2,3].
The time range of interest is 200 ms to be still fast enough in the event of automatic reclosings.
Some of the conventional protection criteria (measuring of voltage and frequency) are not suitable here because mains failures are not quickly enough detected by those. Nearly in all cases the better solution is to use the methods of rate of change of frequency supervision (df/dt) and vector surge (Δυ).
For calculation based estimation of transients during mains failures a system can be splitted into relevant components. There are only some rated data necessary to estimate the characteristic of voltage, angular position and rate of change of frequency df/dt. These calculations have been demonstrated and were checked by means of a mains simulation and real measurements.
Appropriate protection relays are available and these were specificly designed for fast mains decoupling. When knowing the customer related system data, calculation for relay adustment is possible without problem.
As to planning of protection schemes for mains decoupling the following guiding principles are outlined:

- The amplitude of the vector surge is defined by the active load change at the generator during mains failure. For strong active load changes, the vector surge relay is very suitable to ensure fast and reliable decoupling.
- A large relevant reactance between the generator and the relaying point is connected increases the measurable vector surge. This should be taken into account when planning the relay installation place. In block operation, the protection relay should be connected at the mains side of the unit-transformer.
- Simultaneously to the increasing share of motors on the load of the isolated system, the relevant impedance decreases. For such an application a rate of change of frequency relay can be re- commended.
- Very often a combination of vector surge and rate of change of frequency could be adviseable because by this the range for detecting different mains failures conditions is extended and so protection of generators becomes more enhanced.

VII. Literature

[1] L. Fickert, R. Pöschl, Schutztechnische Untersuchungen der Dynamik bei Inselbildungen mit einer Eigenerzeugungsanlage, VEÖ-Journal, 10/95

[2] P. Harrison: Überlegungen zum Aufbau eines Lastabwurfprogrammes, Brown Boveri Mitteilungen 10-80, pages 593-598

[3] R. Berthold, V. Narayan: Lastabwurf und Netztrennung, Brown Boveri Mitteilungen 6/7-81, pages 250-256.