Protection of embedded generation connected to a distribution network and loss of mains detection.

Matthieu GUILLOT, Christian COLLOMBET, Pierre BERTRAND, Bernhard GOTZIG

Schneider Electric, France

The installation of an embedded generator creates specific problems to the Electricity Supply Company responsible for managing the distribution network. Specific documents such as the Engineering Recommendation G59 in the UK or the Technical Guide B61.4 in France address these problems.

The increased number and power of embedded generators connected to the distribution networks changes the characteristics of these networks. As a result, uncoupling protections and generator protections must fit new requirements, both in economical and technical fields.

From a technical point of view, the main requirement is to prevent embedded generators from operating in island mode, thus supplying a section of the public distribution network. Since an increased production capacity can maintain voltage and frequency over a longer period within the limits of traditional uncoupling protections, the latter (under- and over-voltage, under- and over-frequency protections) become insufficient. Moreover, when the number of embedded generators of different size increases, the network's stability and machines are put at risk. There is therefore a need for an efficient protection system.

Embedded generators have only developed because they are cost-attractive. Thus, industrial solutions are developed whilst specific engineering studies are reduced to a minimum. Digital multi-functional relays will contribute towards this objective by offering a simple, easy-to-set and powerful protection system.

This paper outlines how a digital ROCOF (rate of change of frequency) uncoupling protection associated with a loss of synchronism generator protection can ensure both safe uncoupling and optimised continuity of supply. The settings of these protections will be discussed as well as the implications of incorporating different protection elements in a multifunction device.

Protection d'un producteur indépendant raccordé au réseau de distribution et détection de la perte du réseau.

Matthieu GUILLOT, Christian COLLOMBET, Pierre BERTRAND, Bernhard GOTZIG

Schneider Electric, France

L'installation de générateurs pose des problèmes particuliers à la Compagnie d'Electricité qui exploite un réseau de distribution. Des documents spécifiques, comme la recommandation G59 au Royaume Uni ou le Guide technique B61.4 en France ont été écrits pour résoudre ces problèmes.

La croissance en nombre et en puissance des installations de production raccordées aux réseaux de distribution modifie la physionomie de ces réseaux. En particulier, les protections de découplage et les protections des alternateurs doivent être adaptées à de nouvelles contraintes, à la fois techniques et économiques.

Le principal besoin technique est de s'assurer que le producteur indépendant ne peut pas alimenter une partie du réseau public en mode iloté. Une capacité de production accrue pouvant maintenir la tension et la fréquence plus longtemps dans les limites des protections de découplage classiques, celles-ci deviennent insuffisantes. De plus, le nombre et la disparité des tailles des machines raccordées augmentent le risque d’instabilité et de dommage à certaines d’entre elles, donc le besoin de protection.

La génération dispersée ne se développe que parce qu’ elle est économiquement attractive. Les solutions s'industrialisent et les études sont réduites au minimum. Les protections numériques multi-fonction participent à cette évolution en proposant un système de protection simple, facile à régler et plus performant.

Cet article décrira en particulier comment une protection à dérivée de fréquence et une protection des générateurs contre la perte de synchronisme permet de sécuriser le découplage et d’optimiser la continuité de service. Le choix des réglages sera discuté, ainsi que l'impact de l'intégration de ces fonctions dans un relais de protection multi-fonctionnel.

PROTECTION OF EMBEDDED GENERATION CONNECTED TO A DISTRIBUTION NETWORK AND LOSS OF MAINS DETECTION

M. Guillot, C. Collombet, P. Bertrand, B. Gotzig

Schneider Electric, France

INTRODUCTION

The proliferation of dispersed embedded generation has become a fact, and is a real challenge for protection and control systems manufacturers. Indeed the existing offer is not really satisfying. The difficulty is to find the right balance to fulfil utilities requirements to ensure performances and security of the main network, and to offer the customer (the private producer) a comprehensive package easy to set that will eliminate all potential damage to the generators without nuisance tripping.

The purpose of this paper is not to activate the debate about loss of mains (LOM) protection but to describe why the rate of change of frequency (rocof) protection is an efficient and safe solution. We will explicit settings to show how it could helpfully complete classical protections of the point of interconnection. On the other hand phase shift protection will be considered from point of view of generator's protection and compared to loss of synchronism function.

INTERCONNECTION WITH UTILITY NETWORK

The installation of an embedded generator poses certain problems to the Public Electricity Supplier (PES) responsible for managing the distribution network. Specific documents such as Engineering recommendation G59/1 in the UK (1) or the Technical Guide B61.4 in France (2) were introduced to address some of these problems and define parameters that must be satisfied by the installation's protection and control scheme.

These requirements may change from one country to another but generally expectations concerning protections are very similar:

- To disconnect the generator from the PES network if an abnormality occurs that results in an unacceptable deviation of voltage or frequency at the point of supply

- To disconnect the generator from the PES network in the event of loss of one or more phases of the PES supply to the installation

- To disconnect the generator from the PES network in the event of islanded network without fault

Operation of this protection should open the point of interconnection therefore it is normally located on this circuit breaker.

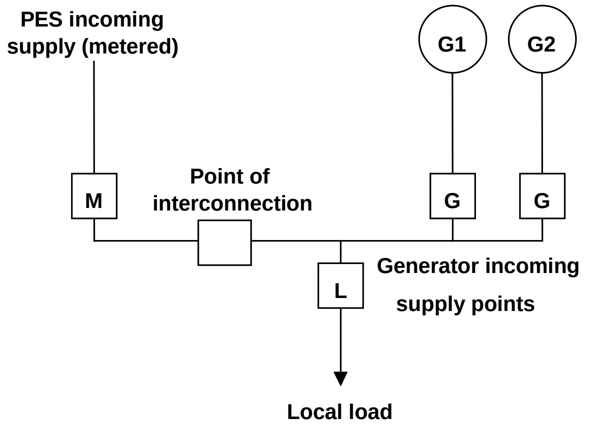

Figure 1: Typical embedded generator installation

These objectives can be met using a protection package that includes the detection of under or over voltage conditions, and under or over frequency conditions.

Where it is possible for part of the PES network to become disconnected from the remaining PES network, but still be connected to the private generator ("islanding situation"), two main risks exist:

- Danger to personnel

- Risk of PES supply being restored out of synchronism with the embedded generator

To avoid these risks, a dedicated loss of mains protection (LOM) may be requested by PES to complete over and under frequency protections.

LOSS OF MAINS PROTECTION

Loss of mains protection suffers from a terrific reputation. In the -almost harmonious- increase in the number of embedded generators, protection remains a major issue beside voltage rise and short-circuit level modification. Both rocof and vector shift protection which are commercially available today are subject to nuisance tripping. Replies to questionnaires in the Preliminary Report of CIRED working Group WG04 Jenkins (3) are self-explanatory. As the manufacturer we have to keep this in mind during the design of the protection.

During a loss of mains condition that leads to islanding, the embedded generator will run without a synchronous reference. If there is a power transfer between the embedded generator and main network before the loss of connection, the frequency of the embedded generator will change. The change in the current provided by the generator will also produce a change in the phase of terminal voltage. Both the vector shift and the rocof protection respond to this condition.

Analogy with mechanical systems

To exemplify these two principles, let's imagine a truck and a small car towing together trailers. (Figure 2)

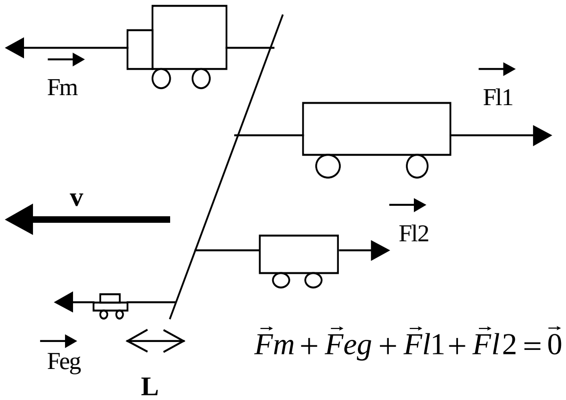

Figure 2: Balanced state - mechanical analogy

When load and drive are balanced the speed is constant. If any link between the truck and the car is broken, the balance of forces is also broken and a rate of change of speed will appear. (Figure 3) The situation of an embedded generator is very similar to that of the small car. In case of loss of mains the chance for new balance situation between load and power is very small. In that analogy, the rate of change of frequency is directly equivalent to the rate of change of speed. The phase shift is equivalent to the length variation of the link between the car and trailers. Just as the mechanical rule is simple the electromechanical equation for synchronous machines is very complex.

This simple analogy shows the difference between two consequences of the LOM: A lasting change of the speed and an "instantaneous" length variation of the link.

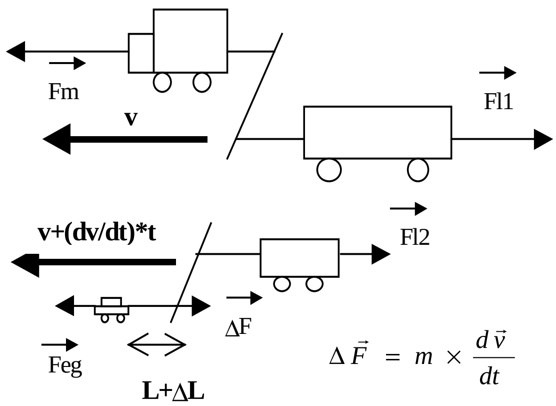

Figure 3 : Loss of mains - mechanical analogy

Relation between rate of change of frequency, phase shift and power variation: For the embedded generator a loss of connection to the main electrical network will produce a variation of the electrical torque. And the rate of change of frequency can be easily related to active power demand variation:

During first few seconds a good approximation is:

$$\frac{df}{dt} = -\frac{\Delta P}{2SnH} f_0$$

ΔP: Power demand variation MVA
H: Inertia constant MW*s/MVA
Sn: Rated power. MVA
f_0: Frequency before LOM

Examples

Rated power	2 MVA	20 MVA
Inertia constant	0.5 s	2 s
Power demand variation	+0.1MVA	+1MVA
Rocof	- 2.5Hz/s	- 0.6Hz/s

In the mechanical system, length variation and rate of change of speed are proportional. For a synchronous generator, the "link" between drive and network is electromechanical and the relation between torque and phase angle is not linear. $\Delta\varphi$ will change like $\Delta P * Xd / 3V^2$. However there is no simple way of calculating phase shift as it depends on pre-fault transit, synchronous and transient reactance, saturation of magnetic circuit, and power factor before and after LOM.

Risk of abnormal operation of LOM protection

The occurrence of short circuits on a feeder close to the generator, network modification, or connection of the generator to the network may cause transient perturbation of voltage phase and frequency.

For example: Simple and frequent phenomenon like coupling the generator to the network even with a small error in phase and frequency will produce a short oscillation of the rotor before synchronisation. LOM protection with sensitive setting can respond to it. This phenomenon's period is generally between 0.5 and 2sec. A time delay of half this pseudo period will ensure stability during transient swings of the generator.

A definite time rocof protection may help to avoid false trip. Phase shift protection will arbitrarily be set (6° or 8°…) and trip instantaneously. Frequency variation may be correlated with system data and last as long as the generator runs alone. A short time delay helps to go through transient instabilities. Faster auto reclosers leave at least 0.3 - 0.5 sec to make a decision. For that reason we have chosen to use a definite time rate of change of frequency protection.

Existing rocof protections are generally based on a phase shift measurement during a time interval. The result is protection that responds to both frequency variation and phase shift. See McDowel (4). Consequently there will be a long time to trip in case of slow variation of frequency, and a high sensitivity to all voltage perturbations. Digital technologies help today to process a true rate of change of frequency measurement.

ROCOF IMPLEMENTATION IN A DIGITAL RELAY

The rocof measurement in Schneider digital protections (Sepam range) is based on well–proven Fourier transform of positive sequence voltage. Harmonics rejection is very good. Positive sequence voltage is not disturbed, when frequency is running out of fundamental as explained by Phadke et al. (5). This measurement is sensitive to initial phase shift, so additional stabilisation has been designed to ensure a safe behaviour during any voltage perturbation which is not a true rate of change of frequency. The rocof calculation needs 3 cycles. The rejection of erroneous values caused by phase shift leads to a tripping time about 100ms.

This algorithm has been extensively tested. Not only in "steady state" condition (Constant df/dt) but also in transient condition with various simulations: Loss of mains in various conditions has been simulated. More comprehensive tests such as fault in the network, loss of synchronism, coupling, load shedding, change in the network topology have also been carried out.

In our algorithm we managed to eliminate the phase shift perturbation. The protection will only respond to the rate of change of frequency according to a definite time characteristic.

ROCOF SETTING GUIDELINE

Embedded generation in itself is not a new subject. What's new is the loss of prerogative of power suppliers on that subject. Change in rules and competitive market have resulted in an increase of embedded capability:

- In case of islanding operation, embedded generators are more able than in the past to keep frequency and voltage within classical protection settings.
- The market requires simple and low cost solutions. Embedded generation does not mean heavy study on stability or on settings…

We will try to provide solutions that are easily applicable to this question.

Yesterday LOM protection was relying on over and under frequency, and over and under voltage. The rocof function designed for Sepam range responds only to frequency variation and has a definite time characteristic. So this protection can be used as a frequency protection. Its main advantage is the response time during slow variation of frequency. (<2Hz/s).

Tripping time of rocof compare to over and under frequency: Under and over frequency protections in embedded generator applications are generally set at f_0 + 0.5Hz and f_0 - 0.5Hz. If we consider that the rate of change of frequency is constant during a loss of mains condition (it's correct in the first few seconds), we can draw the pick-up curve of under and over frequency protection in the (time, Hz/s) plot.

If the rocof (or df/dt) is -0.5Hz/s the under frequency protection set at 49,5Hz will react after one second.

If we assume the response time of Under / Over frequency is 0,1sec the pick-up time of under and over frequency protection is T = 0,5 / (df/dt)+0,1 (sec).

Rocof protection even with a time delay will speed the detection of islanding operation

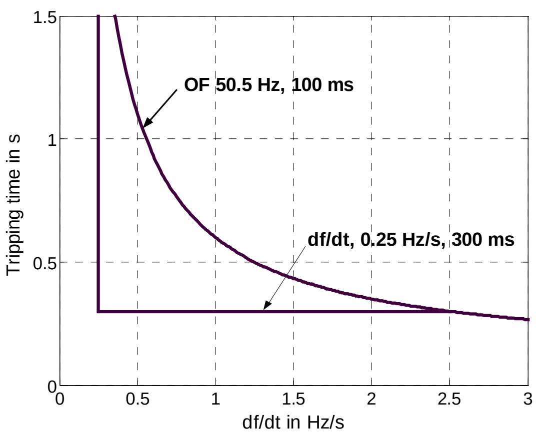

Figure 4: Tripping time curve of over frequency and rocof in the (time, Hz/s) plot.

A symmetrical curve could be drawn for negative rocof and under frequency protection.

Low set choice: To ensure that loss of mains conditions are detected, sensitive settings (<0.5Hz/s) are applied to the rocof protection. Disturbances such as faults, load variations or network modification can also cause frequency swings and, although the calculation of the rate of change of frequency has been carefully stabilised, the rocof protection pick-up setting can be transiently exceeded. To avoid nuisance tripping under these conditions a time delay should be applied.

Where a requirement is specified by the PES, the rocof protection must be set according to this requirement.
If no requirement exists, the rocof protection should be set above the maximum rate of change of frequency occurring on the grid, during healthy system conditions. (Outside the European interconnected network this could be significant). If no such information is available, the low set may be based on generator data using the formula:

$$\frac{df}{dt} = -\frac{\Delta P}{2\,SnH}\; f_0$$

Time delay: For settings lower than 1Hz/s a time delay longer than 300ms is suggested. Above that, shorter delays can be used.

If an auto-reclosing device exists upstream the embedded generator then the loss of mains protection must initiate opening of the intertie breaker during the shortest dead time (generally from 0.5 to 1s or 2s) of the auto-recloser. This imposes an upper limit of the time delay.

A high set may be added to the low set. The benefit of the high set element is that it provides faster tripping than the frequency protections in the event of quick variation of the frequency.

Rocof protection as LOM detection won't be a revolution for the protection of embedded generation. It's very similar to frequency protections already used today. So setting may be chosen using the same principles. Obviously we can use the rocof protection with time delay and get a significantly shorter tripping time in case of slow frequency variations. The time delay ensures stability during transient swings. Phase shift protection will respond to the same situations but will be more difficult to stabilise and to set.

LOSS OF MAINS / LOSS OF SYNCHRONISM PROTECTION

Vector shift protection is sometimes used even when PES does not request such a LOM protection. In fact the generator suppliers generally recommend it without consideration for discrimination and consistence with interconnection protection.

Indeed phase shift measurement is interesting to evaluate the generator perturbation. It's closer to a simple and very sensitive loss of synchronism protection than to a loss of mains protection. Contrary to loss of synchronism protection phase shift protection will trip after first torque impact regardless real network perturbation and chances to get back to synchronism.

For a synchronous generator a power criteria would be better to build a loss of synchronism protection. Redfern and Cheksfield (6) propose to use a three criteria protection based on the real power value, the reactive power value and the rate of real power change.

For example when a fault occurs in the PES network close to an embedded generator, this one experiences instantaneously a sizeable drop of real power as shown in Figure 5. When fault is cleared the real power suffers a period of oscillation characterised by the generator inertia, load conditions before faults, etc. During fault, the generator speed and internal angle increase. According to the fault clearance time the generator may run to pole slipping conditions. In that case, torque oscillations are important and consequently mechanical damages may occur.

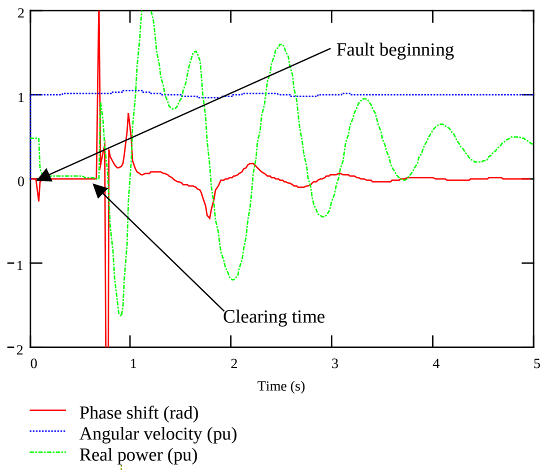

Figure 5: Pole slipping of an embedded generator following a fault on the close PES network.

Phase shift protection response. The phase shift protection will trip before power swing occurs. So the problem is that this type of protection will trip even if loss of synchronism conditions are not met.

On the other hand with a protection based on real power evolution, which is an image of mechanical constraint on the generator, it is possible to detect if pole slipping will occur or not.

To build an efficient loss of synchronism protection avoiding unexpected tripping, two principles can be associated: appropriate equal area criterion based on generator real power, and/or number of generator real power inversions. This kind of protection could be set in order to be as sensitive as a phase shift protection but it could also be more discriminating.

It should be noticed that the rocof protection as described above does not react to that fault. We consider that LOM protection has to react only to islanding condition.

CONCLUSION

The growing number of embedded generators has lead to new technical problems and in particular has reached limits of classical protection for interconnection with the PES. Some of them have chosen to request loss of mains protections. We have designed a function based on rate of change of frequency protection using digital technologies in Sepam range. This function should be used as a frequency protection with improved sensitivity and time response. It would help for detection of islanding condition characterised by slow frequency variations. Discrimination and stability has been ensured and checked since each unexpected separation from PES means loss of money.

The complete protection of the embedded generator point of interconnection includes loss of mains but also several other protections: under or over voltage, under or over frequency, neutral voltage displacement, short-circuit protection... A digital multifunction protection such as Sepam will enable this comprehensive package. Control logic facility allows smart combination of these functions. It may also take into consideration inter-trip order from PES, switch from one setting to another in case of failure of communication channel, and it processes all control functions of circuit breaker.

Standard solutions based on Sepam range including rocof are available for protection of the point of interconnection of embedded generators.

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