Instantaneous Specific Protection Method Against Faulty Synchronizations of Synchronous Machines

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ABSTRACT The probability of faulty synchronization of a generator is very small, but not impossible. The main cause of a faulty synchronization is due to wiring errors caused during maintenance or commissioning when voltage transformer and synchronizing equipment are connected or reconnected wrongly. Faulty synchronizations of synchronous generators cause overcurrent and high electromagnetic torque values that can severely damage, not only the generators their selves, but also prime movers and step-up transformers. Moreover, they produce disturbances on the power system such as power oscillations and voltage sags that can end up collapsing the system if it is not cleared quickly. Despite that, conventional synchronous generator protection systems have not a specific function against faulty synchronizations. This paper presents and analyzes a new and specific protection method against faulty synchronizations. The method is based on an instantaneous low setting overcurrent protection that is only activated during synchronizations. Once the synchronization ends, the protection gets disabled in order to allow the increase of the generator power output. Consequently, it minimizes the damages and the disturbance in the power system through rapid detection and tripping. The method has been successfully validated by computer simulations for a thermal power plant 362 MVA turbo-generator, and by experimental tests on a 5 kVA laboratory generation unit.

INDEX TERMS Power system protection, power system transients, generators.

I. INTRODUCTION

Synchronization is the process of matching frequency, voltage, phase sequence and phase angle of a synchronous generator with an already running electric power system, enabling to couple both. The methods to carry out synchronizations can be manual, assisted manual or automatic. The most commonly used are automatic methods, which include the use of an anticipatory automatic synchronizer (ANSI 25A) and a synchronism-check supervision relay (ANSI 25), usually microprocessor-based [1], [2]. All of these devices perform the duties of governor control, exciter control and breaker closure [1]–[3].

During synchronization or paralleling of generators, dangerous operational faults can occur if any of the synchronization requirements are not fulfilled [4].

Furthermore, synchronization process has proven to be more difficult in the case of distorted or unbalanced power

systems [5], in presence of harmonics [6], in microgrids [7], in power systems with high presence of distributed generation [8], in wind turbine driven generators [9] or grid converters [10], [11].

The synchronization requirements include meeting the same phase sequences and the same or similar voltage amplitude, frequency and phase angle difference at both sides of the generator circuit breaker, in order to ensure the safety of paralleling two systems [1]. If one or more among the aforementioned requirements are not met within an acceptable tolerance window [12], [13], different adverse effects can affect the generator itself and also the rest of the power system.

Under steady state operating conditions, synchronous generators are designed to be highly stable and, even in case of external short-circuits, when they have to supply an overcurrent larger than the rated current, without disconnecting from the grid [14].

However, faulty synchronizations can cause high currents and torques that largely exceed those experienced during
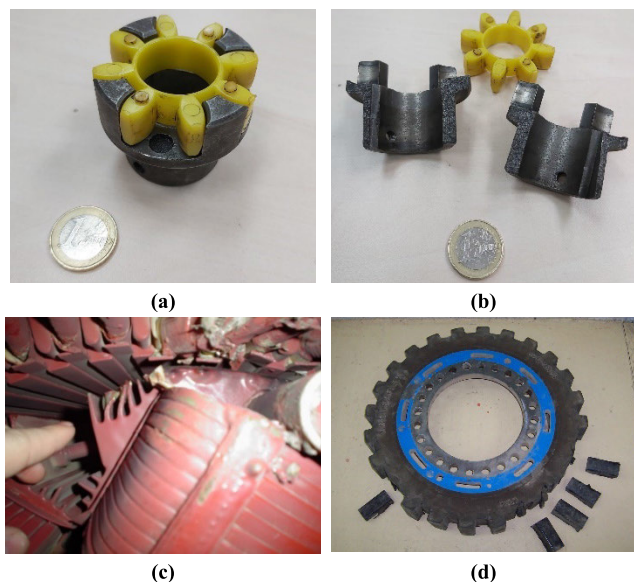
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FIGURE 1. 5 kVA Synchronous generator's rotor shaft flexible coupling before (a) and after (b) a faulty synchronization. 2500 kVA gas engine driven generator after a faulty synchronization. Stator and rotor damages (c) and elastic coupling damages (d).

TABLE 1. Synchronization limits for synchronous generators.

	$\Delta\delta$ [°]	ΔU [%]	Δf [Hz]
IEEE Std C50.12	±10°	+5	0.067
IEEE Std C50.13	±10°	+5	0.067
Manufacturer 1	±7°	±10.7	0.54
Manufacturer 2	±15°	±10	0.50
Manufacturer 3	±15°	±5	0.50

sudden terminal short-circuit, thus severely damaging the generator. Two examples, close to the authors, are shown in Fig. 1.

In both cases the synchronizations were performed with a phase difference of 180°. The 5 kVA machine was incorrectly synchronized in our lab on purpose, afterwards we decided to reduce the voltage for testing. The Fig. 1 shows the elastic coupling before (a) and after (b) the faulty synchronization. The causes of the faulty synchronization in the 2500 kVA gas engine driven generator were due to an error in the connection of the voltage transformers after a main overhaul. It also shows the stator and rotor damages in (c) as well as the damages in the elastic coupling between the gas engine and the generator (d). These out of step synchronizations have dire consequences for both machines because the process did not stop quickly.

Mechanical effects on the generator due to high transient torques and excessive instantaneous currents include loosening of stator winding bracing, and blocking, deformation, cumulative fatigue damage or even cracking of coupling bolts, couplings and rotor shafts [2], [12], [13], [15]. The impulse current could even damage the windings insulation, and the magnetic flux density might be easily saturated at the rotor pole surface, leading to stronger stress on the rotor tooth and damage the turbine generator [16]. This can lead in a reduction of the generator's service life or even in a catastrophic failure depending on the voltages mismatching as shown in Fig. 1.

Nowadays the probability of a faulty synchronization is low thanks to the advancement of synchronizing methods and devices as the presented in [17], but not impossible. The process is usually conducted with help of automatic synchronizers (ANSI 25A) at times supervised by microprocessor-based synchronism-check relays (ANSI 25) [3]. Nevertheless, some faulty synchronizations continue taking place, mostly as a result of wiring connection errors, most commonly in voltage transformers or synchronization equipment, during maintenance or commissioning [18].

The severity of the adverse effects depends on the magnitude of the deviation with respect to the required conditions of phase difference, $\Delta\delta$, frequency difference Δf, and voltage difference, ΔU [15], [19]. Thus, synchronous generators manufacturing standards specify certain tolerable limits regarding all three parameters during synchronization [12], [13], and also manufacturers themselves recommend certain limits (Table 1).

The adverse effects of each parameter exceeding their tolerable limits are the following:

A. EFFECTS OF POOR RMS VOLTAGE MATCHING
This deviation produces a high sudden reactive power flow either into the generator or into the power system, according to the voltage difference sign [20].

B. EFFECTS OF POOR FREQUENCY MATCHING
In case of slip frequency, an acceleration or deceleration of the rotating shaft takes place after connection to match the generator speed with the power system frequency. The transient torque causes instantaneous and cumulative mechanical damage to the generator and prime mover [21].

C. EFFECTS OF POOR PHASE MATCHING
The phase angle between the generator and the power system voltage phasors is related to the position of the rotor with respect to the magnetic field produced by the stator three-phase currents. Therefore, if a phase difference, $\Delta\delta$, exists, the rotor suddenly tries to change its position after connection, either accelerating or decelerating. This produces transients of high torques and currents, which can severely damage the generator rotor and the prime mover.

The worst attainable failure appears when synchronization is performed at 150° or 180° (out of phase synchronization) [15]. It commonly results from voltage transformer wiring errors or synchronizing system failures [18], [20]–[23]. In this case, the generator's damages can be catastrophic. The shaft and prime mover can be critically damaged. Additionally, stator and transformer windings are susceptible to be also damaged from high currents [12], [13].

If this fault happens, the generator will require expensive repairs or replacements of some of its pieces, especially for the rotor [13], [22], thus incurring in overall large monetary losses. Finally, disturbances can be caused in the power system, such as power oscillations and voltage deviations from nominal [24].

The severity of the adverse effects also depends on the ratio between the rated power of the generator and the short-circuit power of the electric network, and even on the rotor design [23].

Despite all negative effects described above, there is no specific protection function to trip generation units instantaneously in the case of faulty synchronization.

Two of the abnormal operating condition protective elements associated with synchronizing problems are reverse power protection (ANSI 32) and loss-of-field protection (ANSI 40). Both protections have a time delay [2], [25]. The usual practice is synchronizing with slightly positive slip and with a slightly larger generator voltage with respect to the bus voltage. Thus, reverse power and loss-of-field protection trips are avoided, respectively.

The differential protections (ANSI 87G) do not trip because there is no difference between the currents on both sides of the stator or step-up transformer windings [26], [27].

Stator–ground fault protections (ANSI 59N) do not trip because no current flows through the ground [28].

Overcurrent protections do not trip instantaneously because synchronous generators must supply overcurrent in case of external short-circuits. Overcurrent protection (ANSI 51) is usually a back-up protection for external faults, so the trip is delayed [25].

Under-impedance protection is normally used as back-up protection for external and internal faults as well. It is a usual practice to set this protection at 0.8 p.u. / 3 s for external fault back-up protection and at 0.8 Z_T / 250 ms for internal fault back-up protection [25]. Where Z_T is the impedance of the transformer. In case of out of phase synchronization they could trip but not fast enough to limit the damages [22].

The asynchronous operation of the generator in case of a loss of synchronism can produce severe damages [25]. There is a specific protection to detect this phenomenon, pole slip or out-of-step protection (ANSI 78). However, in case of a faulty synchronization the mechanical power supplied by the turbine is not enough to produce the asynchronous operation of the generator.

The Table 2 shows a summary of the generator protection functions in case of faulty synchronization. The proposed method is also included at the end of the Table.

Although the probability of faulty synchronization is very small, it can, and it does occur. In Table 3 some major failures have been collected from [18], in which severe damages have been caused from out of phase synchronization and inadvertent energization failures per number of generators.

The generators' average age that participates in [18] is 30 years.

TABLE 2. Synchronous generators protection functions in case of faulty synchronization.

ANSI	Description	Trip
21	Under-impedance	Time delayed
32	Reverse power	Time delayed
40	Loss of excitation	Time delayed
50/27	Inadvertent energization	No trip
51	Overcurrent	Time delayed
51N/59N	Stator ground fault	No trip
78	Pole slip protection	No trip
87	Differential protection	No trip
	Proposed Method	Instantaneous Trip

TABLE 3. Synchronization failures and inadvertent energization in synchronous generators [18].

Country	Out-of-phase failures/Generator	Inadvertent energizations/Generator
Croatia	3/6	0/6
Finland	0/15	0/15
India	0/4	1/4
Ireland	1/1	1/1
Mexico	0/4	0/4
Norway	0/1	0/1
Spain	2/4	0/4
Serbia	0/1	0/1

As the generator protection system does not have a specific synchronization protection function, the overcurrent transient will last for several cycles, even seconds, until steady state is reached or the underimpedance relay trips, in most of the cases with several damage to the generator and a large impact on the power system.

In conclusion, synchronization is a critical process which is usually well performed. But, in case of faulty synchronization, the damage, especially to the generator, can be extremely devastating. Moreover, none of the conventional protection functions are specific designed to trip instantaneously the synchronous generators in the event of faulty synchronizations [25], [26], [29]–[31].

This paper presents a new, simple and economic protection method for synchronous generators against faulty synchronizations based on a low-setting, instantaneous overcurrent protection. This protection is only enable during the synchronization process. The main target of this protection is to trip the generator as fast as possible, minimizing the generator's damages in case of faulty synchronization. The method has obtained the grant of a European Patent [32].

II. OPERATIONAL PRINCIPLE OF THE NEW PROTECTION METHOD

During synchronization, just after the breaker is closed, generator currents are in practice below 30–50% of the rated current. After the generator breaker closes, the operation modes change from speed to active power and from voltage to reactive power in the governor and automatic voltage

regulator (AVR) respectively. At that moment the active and reactive power set points are close to zero. So, after several cycles, steady state is reached, and the generator currents are very low, close to zero.

Afterwards, the usual practice is to increase the active and reactive power up to the rated or desired operating point of the synchronous generator. This is considered to be a correct synchronization, but it depends on the accuracy of the automatic synchronizer, or on the operator performance, if the synchronization is carried out manually.

In contrast, during a faulty synchronization, generator currents attain greater values due to the voltage, frequency or phase differences. In some cases, such as 150° or 180° out-of-phase synchronizing in large short-circuit capacity power systems, the mentioned currents exceed by far the short-circuit current.

Even if efforts are made to prevent faulty synchronizations, this situation can be produced by various factors. The most frequent case is a wiring error produced during commissioning or maintenance, most commonly at the secondary side of the voltage transformers.

This new method is designed to provide generator protection when the generator is synchronizing. It is based on an instantaneous overcurrent protection, which is only enabled during the synchronization process. The setting of the instantaneous overcurrent protection parameter I_{SET} should be adjusted above the normal synchronization current (<1 p.u.). The protection is disabled in an adjustable time T_{SET} (around 1–2 s) after the generator breaker is closed in order to allow the power output increase. In this way, reliable necessary protection is provided through rapid detection and tripping in case of faulty synchronization [32], [33].

The proposed new method establishes two different settings. First, a current threshold (I_{SET}), that should be fitted above the current attained in a correct synchronization. And then, the time delay value (T_{SET}), that disables the instantaneous overcurrent protection after the generator breaker is closed by means of an off-delay timer.

In this way, the generator breaker will open as fast as possible if current values are greater than I_{SET}, and the synchronization process will be aborted.

Once the breaker closing is detected by the protection, if the current is smaller than the threshold value ($I < I_{SET}$) along the set delay time ($T = T_{SET}$), the protection is disabled. The protection's settings are presented in Table 4.

Once T_{SET} is exceeded, the active and reactive power are increased to reach the rated power output of the synchronous generator. This time should be coordinated with the governor to avoid unwanted trips, especially in generator that increase their load quickly. In Fig. 2 the logical layout of the new protection method is presented.

The inadvertent energization protection (ANSI 50/27) is based on an instantaneous overcurrent protection (ANSI 50) and an under-voltage protection (ANSI 27). In the event of detecting a current value greater than the threshold (10 % of the rated value), this protection detects that the generator

TABLE 4. Synchronization protection settings.

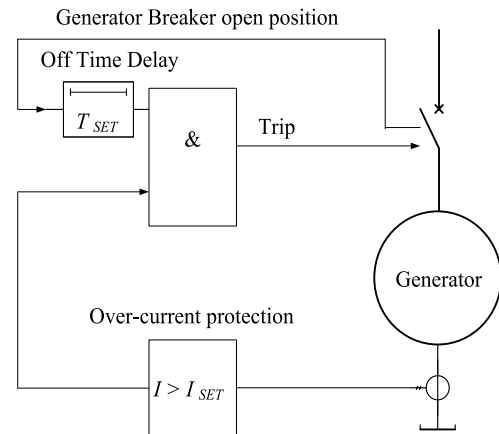| Parameter		Value	Units
Instantaneous overcurrent setting	I_{SET}	0.3-1	p.u
Deactivation time (after closure of generator breaker)	T_{SET}	1-2	s

FIGURE 2. Synchronization protection layout.

breaker has been closed inadequately. Usually, this protection is enabled when the generator is not running (at standstill condition or on turning gear) and it is disabled when the generator output voltage attains approximately 80% of the rated value. So, in case of faulty synchronization, it does not trip the breaker.

With the aim to summarize the method, Fig. 3 shows a theoretical example of the method with a current threshold of 0.5 I_N. The 50/27 protection function is included. As it can be seen, with the proposed method, the protected zone during synchronization process is highly extended.

III. SIMULATIONS

Numerous simulations have been performed to validate the new protection method. A 362 MVA turbogenerator was selected, it is modelled as a round rotor synchronous machine pu standard Matlab-Simulink® block. The generator has a turbine governor and an automatic voltage regulator AVR. The generation unit is connected to a 400 kV power system through a main power transformer, modelled as a two-winding three-phase transformer block. The system data are shown in Appendix, (Tables 5-8) and the simulation model is shown in Fig. 4.

Some simulations are presented in this paper for correct and faulty synchronizations, which are discussed below.

A. CORRECT SYNCHRONIZATION SIMULATIONS

Initially, correct synchronizations are presented taking into account the limits proposed by manufacturer 2 (Table 1). The generator employed in these simulations, which parameters are available in Appendix Table 5, has been made by manufacturer 2.
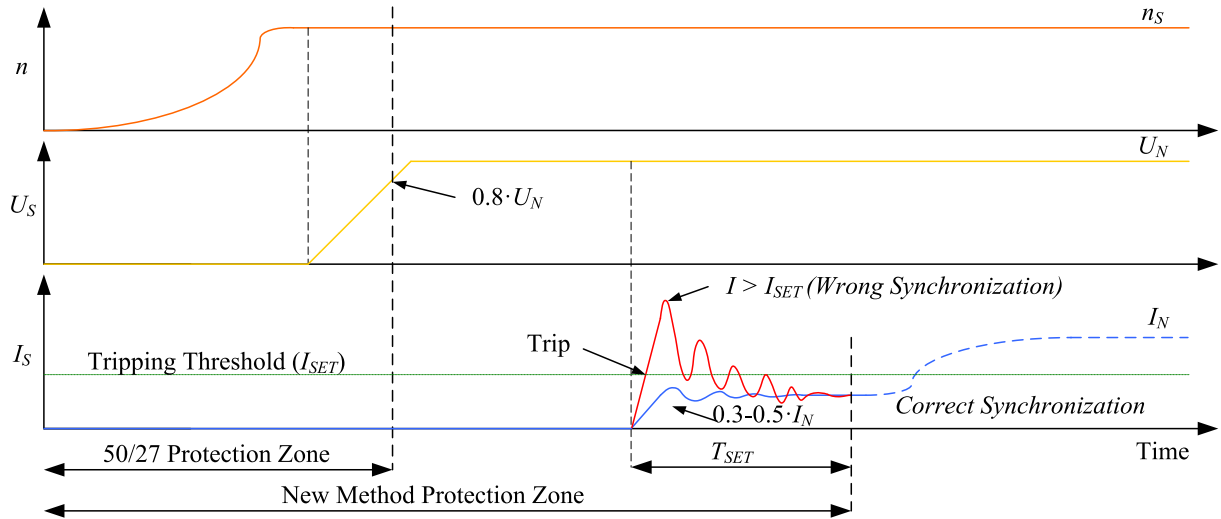
FIGURE 3. Theoretical example of the proposed method operation [n: rotor speed; U_S: stator voltage; I_S: stator current].
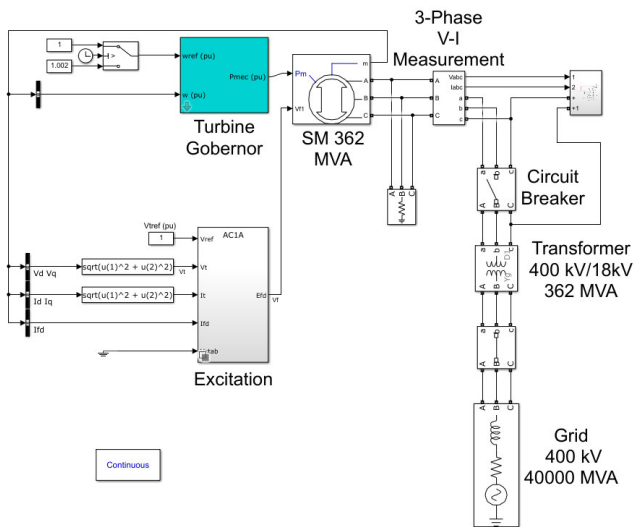

FIGURE 4. Computer simulation model of a 362 MVA turbogenerator synchronization to a 400 kV power system.

FIGURE 5. Computer Generator synchronization currents [$\Delta\delta = 15°$, $\Delta U = 10\%$, $\Delta f = 0.5$ Hz].

In a first case, Fig. 5 shows the currents during synchronization just within the limits recommended by manufacturer 2 ($\Delta\delta = 15°$, $\Delta U = 10\%$ and $\Delta f = 0.5$ Hz) in order to evaluate the rated conditions. As expected, the currents almost reach the generator's rated values in the first peak, and they become attenuated completely after 200 ms.

Next, currents during a synchronization considered satisfactory in practice (all parameters remaining within a typical tolerance window) are presented in Fig. 6 (studied case: $\Delta\delta = 5°$, $\Delta U = 2\%$ and $\Delta f = 0.2$ Hz). In this simulation, as the differences in phase, voltage and frequency are deeply inside the limits, the currents achieved are lower. Therefore, these values have been chosen in the simulations plotted in Fig. 6. The currents in this case attain 0.34 p.u. after
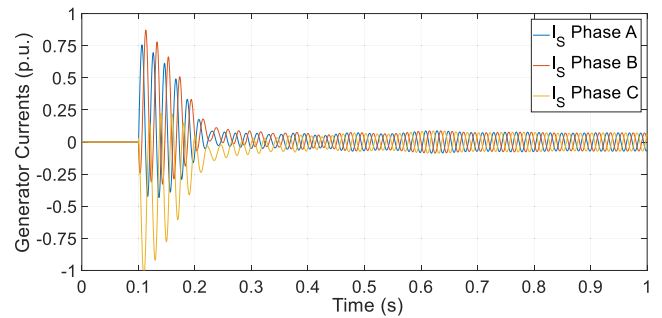
the breaker closure at t = 86.7 ms. For this case, the overcurrent protection does not register high currents at any moment.

In a third case presented in Fig. 7, voltages on both sides of the breaker are identical, phase difference is zero, frequency difference is 0.1 Hz and the generator speed is 3006 rpm ($\Delta\delta = 0°$, $\Delta U = 0\%$, $\Delta f = 0.1$ Hz and $n = 1.002$ p.u.). This situation is one of the most favorable for a correct synchronization. In Fig. 7, it can be observed that, after the breaker closure at t = 128.2 ms, generator current peaks attain 5.4 % of the rated current. As it can be seen, if a correct synchronization is carried out, the transient provoked in the generator is negligible.

Additionally, in Fig. 8, the electromagnetic torque, T_M, attains 8.2% of the rated torque.

The small transient provoked after the correct synchronization can also be noticed in Fig. 9, where the generator speed is represented. It should be remarked that 1 s after the breaker closure the generator reaches steady state.

Then, it is proved that a correct synchronization to grid can have negligible transients for the generator and for the grid (See figures 5 to 9).
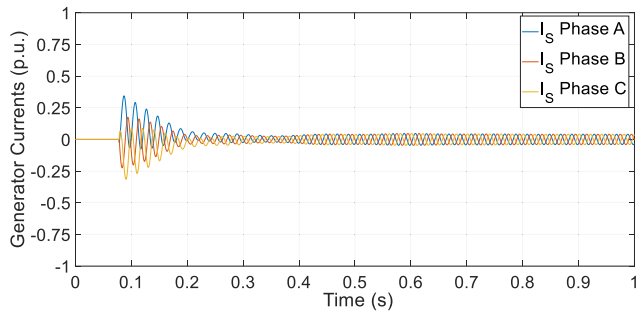
FIGURE 6. Generator synchronization currents [Δδ = 5°, ΔU = 2%, Δf = 0.2 Hz].
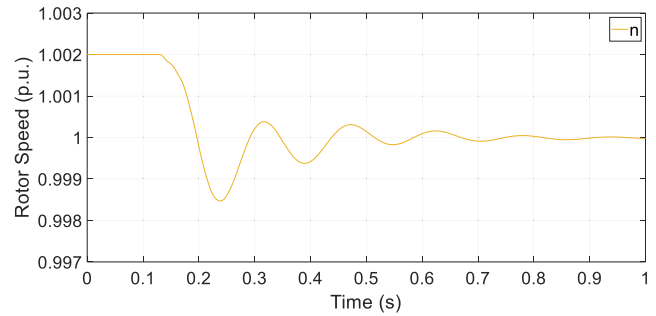
FIGURE 9. Generator speed during a correct synchronization [Δδ = 0°, ΔU = 0%, Δf = 0.1 Hz].
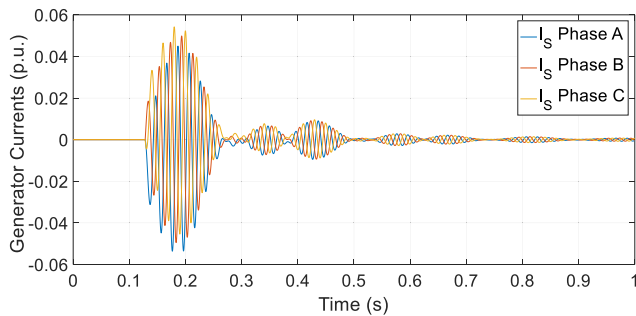
FIGURE 7. Generator synchronization currents [Δδ = 0°, ΔU = 0%, Δf = 0.1 Hz].
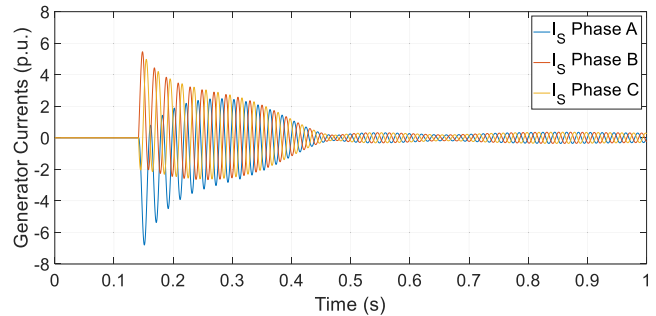
FIGURE 10. Generator currents during a faulty synchronization [Δδ = 180°, ΔU = 0%, Δf = 0.1 Hz].
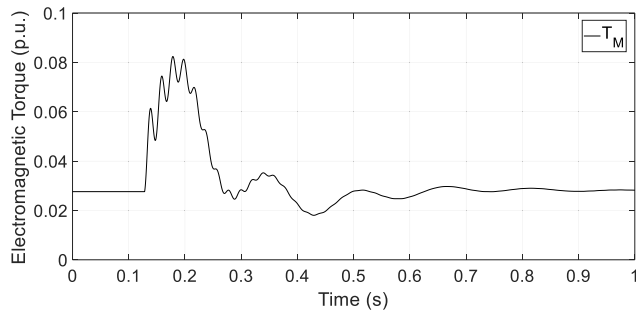
FIGURE 8. Generator electromagnetic torque during a correct synchronization [Δδ = 0°, ΔU = 0%, Δf = 0.1 Hz].
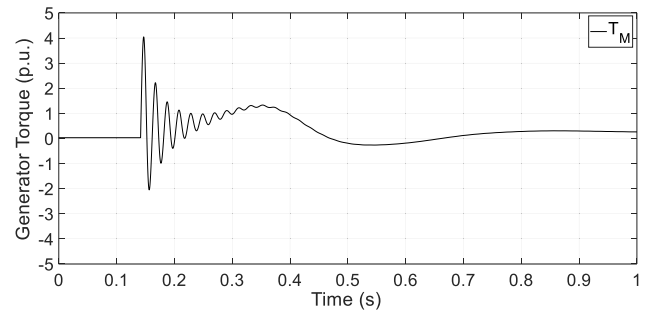
FIGURE 11. Generator electromagnetic torque during a faulty synchronization [Δδ = 180°, ΔU = 0%, Δf = 0.1 Hz].

B. FAULTY SYNCHRONIZATION SIMULATIONS

Once simulated that the system responds correctly to correct synchronizations, a faulty out-of-phase synchronization (180° phase difference) is presented in the following simulations, to analyze the electrical effects that it can cause in the generator.

In these simulations, there are no changes in other parameters, voltages on both sides of the breaker are identical and the frequency difference is only 0.1 Hz ($\Delta U = 0\%$, $\Delta f = 0.1$ Hz). The analysis of the phase angle is the main parameter affected when wiring errors appears.

Seeing Fig. 10, once the breaker is closed (t = 140 ms), generator currents reach 679.8 % of the rated current and it became attenuated to 1 p.u. after 261.8 ms after synchronizing. On the other hand, the electromagnetic torque reaches

401.9 % of the rated torque (See Fig. 11). The transient after synchronization can be also seen in Fig. 12 where the generator speed is represented. As it can be seen, 783.8 ms after the breaker closure, the speed returns to steady state.

The next simulation corresponds to the same case of out-of-phase synchronization at 180° (Fig. 13 and Fig. 14). In this case the protection method presented in this paper is enable. Taking into account the generator's breaker opening time (50 ms) and the overcurrent tripping time (10 ms), the actuation time-delay is simulated as 60 ms. The current threshold value has been set at $I_{SET} = 0.5$ p.u.

Thanks to the overcurrent protection's trip, time with high currents at the generator terminals, and also torque oscillations, are reduced from 261.8 ms to 60 ms (Fig. 12 and Fig. 13), a valuable time that can minimize the damages of the generator.

FIGURE 12. Generator speed during a faulty synchronization [$\Delta\delta = 180°$, $\Delta U = 0\%$, $\Delta f = 0.1$ Hz].

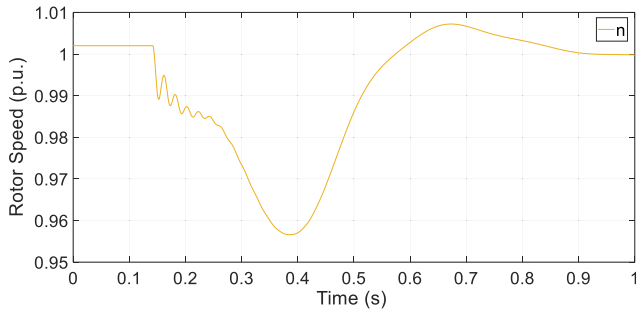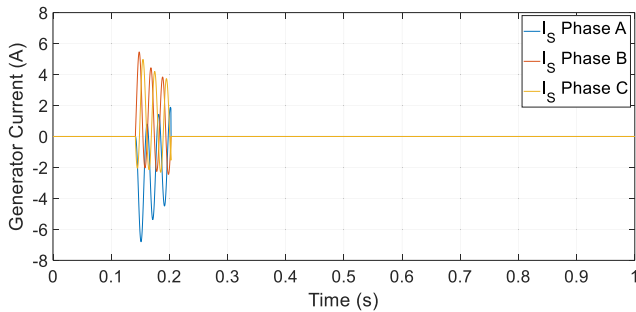**FIGURE 13.** Generator currents during a faulty synchronization [$\Delta\delta = 180°$, $\Delta U = 0\%$, $\Delta f = 0.1$ Hz]. Total tripping time 60 ms.
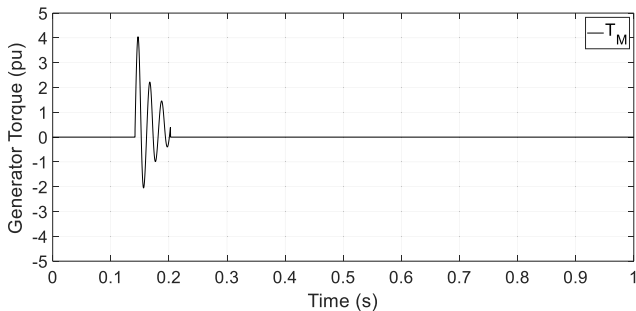

FIGURE 14. Generator electromagnetic torque [$\Delta\delta = 180°$, $\Delta U = 0\%$, $\Delta f = 0.1$ Hz].

FIGURE 15. Simplified single line diagram of the experimental setup.

FIGURE 16. Experimental setup.

IV. EXPERIMENTAL RESULTS

In order to verify the new protection method, numerous laboratory tests have been performed on a 5 kVA generation unit.

A. EXPERIMENTAL SETUP

The simplified single-line diagram and the laboratory experimental setup are shown in Fig. 15 and Fig. 16, respectively.

The tests were conducted on a 5 kVA four-pole synchronous generator (1). The generator is driven by an induction motor (2), fed by a frequency converter (3), while the excitation is fed by a DC power supply (4). The connection to the grid is performed through a 5 kVA power transformer (5). The grid side winding of the AC power transformer is linked to an adjustable three-phase voltage power supply (6).
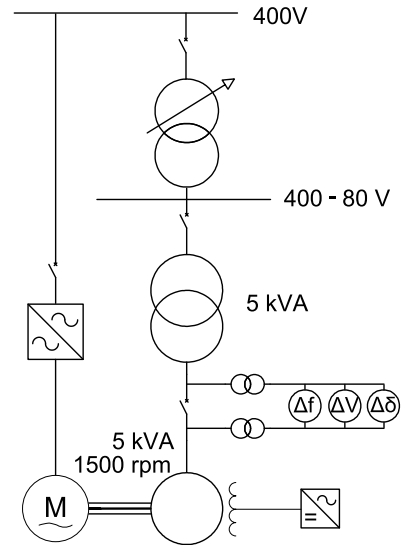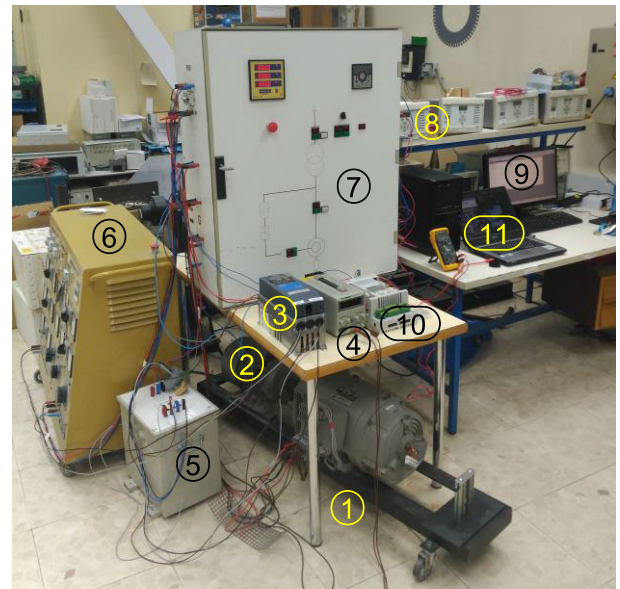
Therefore, it is possible to reduce the power system voltage. This allows to perform faulty synchronization tests at reduced voltage, in order not to damage the generation unit. This action was taken into consideration to avoid severe damages in the testing generator, especially during non-protected tests. (See Fig. 1a and Fig 1b).

The generator circuit breaker, current transformers and voltage transformers are included in a switchgear assembly (7). A MiCOM P343 digital multifunction relay (8) is used as instantaneous overcurrent protection and also as a fault recorder through a computer (9). Finally, an automatic voltage regulator ABB Unitrol 1020 with digital synchronizer (10) is used to perform the synchronization at different conditions, also with a computer (11).
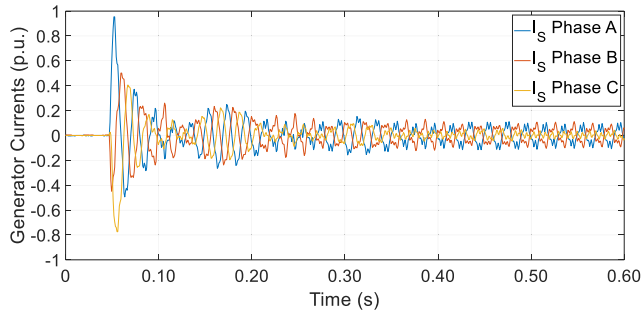
FIGURE 17. Generator currents, I_S, during a correct synchronization [$\Delta\delta = 15°$, $\Delta U = 0\%$, $\Delta f = 0.1$ Hz].

Detailed data of the synchronous generator is included in Table 8 of the Appendix.

B. EXPERIMENTAL RESULTS

Many synchronization tests have been performed for different synchronization conditions ($\Delta\delta$ / ΔU / Δf) as described below.

1) CORRECT SYNCHRONIZATION TESTS AT RATED VOLTAGE (100% / 400 V)

In these tests, satisfactory synchronizations have been performed. As expected, if the ideal paralleling conditions are met ($\Delta\delta \approx 0°$, $\Delta U \approx 0\%$, $\Delta f \approx 0$ Hz), generator currents, I_S, during synchronization are negligible. As the parameter values diverge from the ideal synchronization values at the synchronization instant, the currents increase.

Also, some tests near the limits of the tolerance windows recommended by the manufacturers 2 and 3 (Table 1) were performed. Fig. 17 shows an example of synchronization ($\Delta\delta = 15°$, $\Delta U = 0\%$, $\Delta f = 0.1$ Hz). In this case, currents attain the rated current values just after the closure of the breaker, and after a transient, the current is stabilized at 0.1 p.u. approximately. This value corresponds to the active power supplied by the induction motor fed at 50.10 Hz, while it turns at 1500 rpm. In general, it can be concluded that, at the limit conditions for synchronization, current peaks after the closure of the breaker are near to the rated values. Nevertheless, short-circuit power of the network and short-circuit impedance of the main power transformer have influence on the currents' values.

2) FAULTY SYNCHRONIZATION TESTS AT REDUCED VOLTAGE (20% / 80V)

In the faulty synchronization tests, the bus voltage has been reduced through an adjustable power supply, avoiding any damage on the tested generator. The voltage value has been selected so as not to exceed excessively the rated current of the generator. After some attempts, the value of 20 % (80 V) was selected.

Although reduced voltages have been used for faulty synchronizations, the results are similar to those obtained in a large turbo-generator thermal power plant at rated voltage.
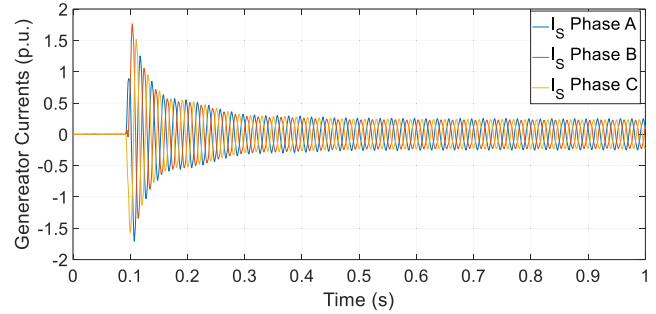

FIGURE 18. I_S during a faulty synchronization at reduced voltage [$\Delta\delta = 120°$, $\Delta U = 2\%$, $\Delta f = 0.1$ Hz, $U = 20\%$ (80V)].
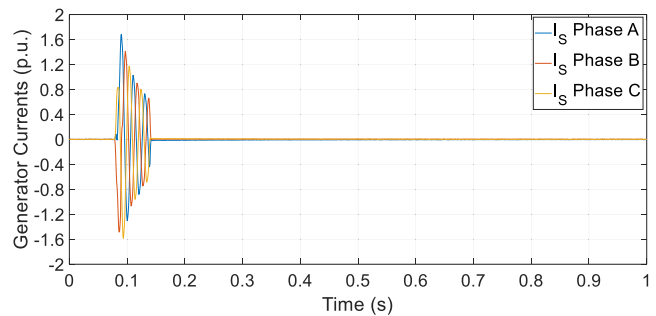

FIGURE 19. I_S at faulty synchronization with reduced voltage and the overcurrent protection in operation [$\Delta\delta = 120°$, $\Delta U = 2\%$, $\Delta f = 0.1$ Hz, $U = 20\%$ (80V)].

Likewise, if the voltages are significantly reduced (5 times lower than the rated voltage), the currents will be reduced in approximately the same proportion.

The rest of the paralleling conditions are met accurately (ΔU and Δf), so the faulty conditions simulate an error in the wiring of the automatic synchronizer.

The tests were implemented with and without the proposed protection. A selection of three cases with $\Delta\delta$ of 120°, 150° and 180° (out-of-step) are discussed.

First, Fig. 18 shows the currents of the generator in the case of a 120° phase error ($\Delta\delta = 120°$), while the voltage difference ($\Delta U = 2\%$) is set at 2 % and the frequency difference at 0.1 Hz ($\Delta f = 0.1$ Hz). In this case, currents attain 1.76 p.u. after closing the generator breaker at t = 98.9 ms, even at 20 % of the rated voltage. After a transient, current is stabilized at 0.18 p.u. approximately.

After, Fig. 19 corresponds to the same test performed at the same conditions but with the proposed protection in operation. The relay tripping time is 8 ms and the total fault duration lasts 62.8 ms (54.8 ms corresponds to the breaker opening time). The current threshold is set at $I_{SET} = 0.3$ pu.

In Fig.19, It can also be observed that the effects of the faulty synchronization on the armature windings and on the power system are rapidly reduced.

In a similar way, Fig. 20 presents the currents of the generator in the case of a 150° phase error ($\Delta\delta = 150°$), while the voltage difference is set to 2 % ($\Delta U = 2\%$) and the frequency difference to 0.1 Hz ($\Delta f = 0.1$ Hz).
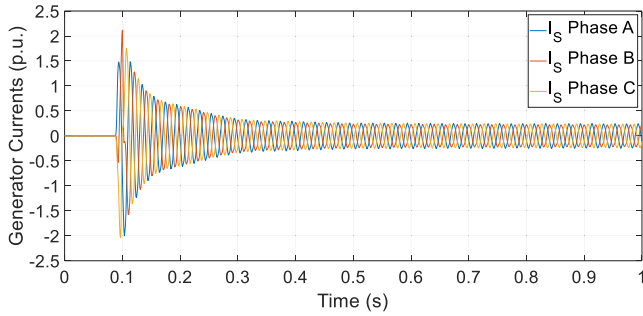
FIGURE 20. I_S at faulty synchronization with reduced voltage [$\Delta\delta = 150°$, $\Delta U = 2\%$, $\Delta f = 0.1$ Hz, $U = 20\%$ (80V)].

FIGURE 21. I_S at faulty synchronization with reduced voltage and the overcurrent protection in operation. [$\Delta\delta = 150°$, $\Delta U = 2\%$, $\Delta f = 0.1$ Hz, $U = 20\%$ (80V)].
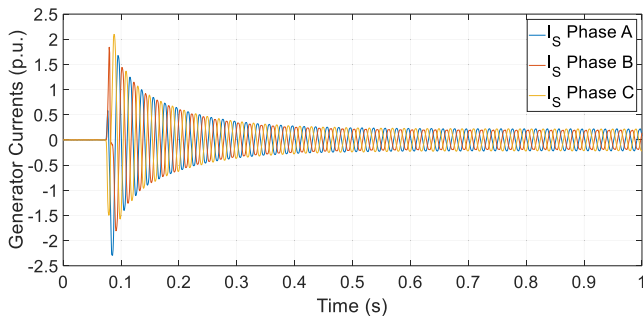
FIGURE 22. I_S at faulty synchronization with reduced voltage [$\Delta\delta = 180°$, $\Delta U = 2\%$, $\Delta f = 0.1$ Hz, $U = 20\%$ (80V)].

Fig. 21 corresponds to the same test performed at the same conditions ($\Delta\delta = 150°$) but with the proposed protection in operation.

As expected, as the phase difference is larger, generator currents after closing the breaker are also larger. In this case, they reach 2.18 p.u. If the protection is in operation, the generator is disconnected quickly in a similar time of 61 ms, when the currents still having values around 1 p.u (5 times higher at rated voltage).

Finally, out-of-step synchronizations with a phase error of 180° ($\Delta\delta = 180°$) without and with the protection in operation are presented in Fig. 22 and Fig. 23, respectively. In these cases, the current peaks reach 2.35 p.u. In this case, the instantaceous overcurrent protection trips when the currents still being higher than 1 pu.
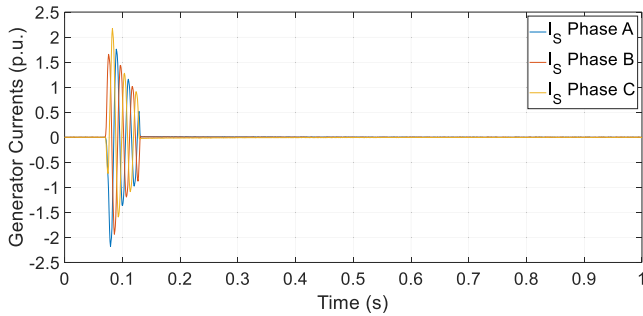

FIGURE 23. I_S at faulty synchronization with reduced voltage and the overcurrent protection in operation [$\Delta\delta = 180°$, $\Delta U = 2\%$, $\Delta f = 0.1$ Hz, $U = 20\%$ (80V)].
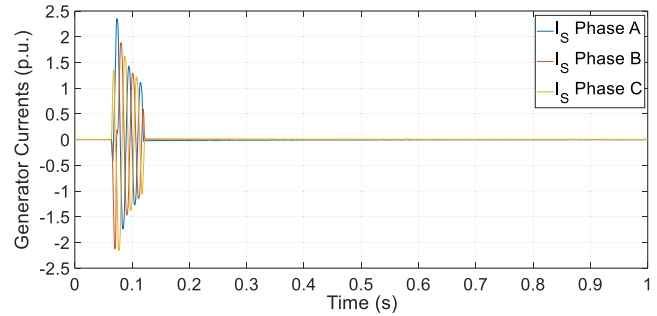
As it can be clearly observed, the bigger the errors in angle during synchronization, the larger the currents and the possible damages. What is more, errors can accumulate and result in altogether in extremely dangerous conditions for the generator.

In this respect, if the synchronization process is considered to be linear, as it is not affected by saturation, in the case of the laboratory generator, currents of more than 10 p.u. could be reached in the case of an out-of-step synchronization at rated voltage.

This situation could not only produce severe damage to the generator unit, but could also cause problems on the power systems, such as tripping of other generators, oscillations, voltage sags, etc.

Nowadays, there are no protections able to avoid the first current peak in a faulty synchronization. However, a fast actuation of an instantaneous overcurrent protection can minimize expensive loses by cutting off these currents rapidly.

V. CONCLUSION

Nowadays there is no specific generator protection function that trips instantaneously in the event of a faulty synchronization. For this reason, this paper presents a new specific protection based on an instantaneous overcurrent protection with a low current setting (lower than the generator rated current), that is only enabled during the synchronization process, and then disabled to allow the increase of the generator power output.

The proposed protection tries to trip the generator as fast as possible, aborting the synchronization process, when excessively high currents flow through the generator after the breaker closure, minimizing the damages.

Numerous simulations of a 362 MVA thermal power plant turbo-generator and many experimental tests in a 5 kVA generation unit were performed. The satisfactory operation of the proposed protection method has been validated through both approaches achieving actuation times of 50-60 ms which is five times lower than other protection methods.

This protection can be implemented into a commercial relay by only inserting the logic algorithm on it, making the method very easy to perform.

The proposed method requires the relay's computation and actuation time, which implies that the first current and torque

peaks cannot be avoided. However, this protection method could minimize the damages in case of faulty synchronization and the perturbation to the power system by stopping the synchronization process as fast as possible. This damage minimization objective (both for generators and for the grid) opens new further works in order to study faulty synchronizations in high power synchronous generators with this new protection installed, taking into account the specific reactances of these generators.

APPENDIX

TABLE 5. Characteristics of the synchronous generator used in simulations.

Rated apparent power	362	MVA
Rated power factor	0.8	
Rated voltage (± 7.5%)	18	kV
Frequency	50	Hz
Rated speed	3000	rpm
Direct-axis synchronous reactance X_d	2.580	p.u.
Quadrature-axis synchronous reactance X_q	2.505	p.u.
Direct-axis subtransient reactance X'_d	0.455	p.u.
Direct-axis subtransient reactance X''_d	0.313	p.u.
Quadrature-axis subtransient react.e X''_q	0.348	p.u.
D-axis transient open-circuit time constant T'_{do}	6.27	s
D-axis transient short-circuit time constant T'_d	1.11	s
D-axis subtransient short-circuit time const T''_d	20	ms
Rated field current I_{fn}	2803	A
Rated field voltage U_{fn}	492	V
Inertia coefficient $H(s)$	1.058	

TABLE 6. Generation transformer unit used in simulations.

Rated power	362 MVA
Winding connection	YNd11
Ratio	411 kV ± 15 x 1 % / 18 kV
Load losses	0.12 %
Non-load losses	0.01 %
Non-load current	0.45 %
Short-circuit impedance	13.05 %

TABLE 7. Power system 400 kV used in simulations.

Three-phase short-circuit	40,000	MVA
X/R ratio	10	
Ground fault level	57.73	kA

TABLE 8. Characteristics of the alternator used in the experimental tests.

Alternator type	Synchronous	3 phases
Rated power	5	kVA
Rated speed	1500	rpm
Rated voltage	400	V
Rated frequency	50	Hz

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