FERRORESONANCE

In power systems, ferroresonance is defined as a forced oscillation between a nonlinear inductance, usually a saturable magnetizing reactance of a transformer, and a capacitor. When the magnetic flux in the nonlinear inductive element reaches its saturation value, the corresponding magnetic reactance of the inductive element sharply drops, which causes the capacitor to discharge, at a faster rate, into it. The circuit is then from this point on in a ferroresonant mode. The capacitance can represent an actual power factor correcting element, a cable's conductor-to-shield capacitance, a surge suppressing capacitor, or, as is shown later, an external reactive power source element required by induction generators, used in nonutility plants, to establish their rotating magnetic field. This forced oscillation can take place when an abnormal situation occurs, for example, the occurrence of a single-line or a double-line-to-ground fault followed by the operation of a single-pole switching device. The equivalent circuit resulting from this may show the nonlinear inductive element to be in series, in parallel, or in a series–parallel combination with the capacitive element. Germay et al. (3) have shown that these circuit configurations can produce ferroresonance at subharmonic, fundamental, or harmonic frequencies. The immediate consequence of these complex oscillating modes between the nonlinear inductance and the capacitance is the appearance, between the faulted phases and ground, of high and sustained ferroresonant overvoltages, which can be harmful for the insulation integrity of all the equipment involved.

Ouhrouche et al. (8) have shown, using an Electromagnetic Transients Program (EMTP), that ferroresonant overvoltages can also occur during islanding of a nonutility induction generator (NUIG), whose unit transformer secondary is opened or lightly loaded, from the main utility. This result is attributed, as first shown in the pioneering work of Gish, Feero, and Greuel (4), to the self-excitation phenomenon of the induction generator.

Both single-phase and three-phase circuits can experience ferroresonance. Certain three-phase circuits can be treated as three different single-phase circuits. The ferroresonance is then called "single-phase ferroresonance." However, if a three-phase transformer whose primary is ungrounded is involved, the three-phase circuit should be considered as a whole system. The ferroresonance is then called "three-phase ferroresonance."

In the following sections, ferroresonance caused by one or two open conductors in power distribution systems will first be considered. The principal and required conditions for its occurrence will be introduced. Secondly, ferroresonance caused by "islanding" of an NUIG from the main utility will also be presented. Since the phenomenon involves nonlinear elements, a mathematical treatment of the problem is extremely tedious. Thus, all the results given in this paper are obtained by using an Electromagnetic Transients Program (1), a powerful tool used in the Power Engineering Community to study many types of transient electromagnetic phenomena.

FERRORESONANCE CAUSED BY OPEN CONDUCTORS

As stated previously, the open conductor conditions can occur from the operation of a single-phase interrupting device such as a fuse or a single-pole recloser following, for example, a single-line-to-ground or a double-line-to-ground fault. Figure 1 shows one of the commonly used circuits for investigating the basic phenomenon of ferroresonance. The capacitors represent an actual power factor correcting element, a cable-to-shield capacitance element, and so on. The other circuits susceptible to experience ferroresonance are those where the primary of the transformer is not grounded (delta or ungrounded wye for three-phase transformers). The secondary of the transformer is either opened or lightly loaded. If one or two phases of the circuit of Fig. 1 should open, one can demonstrate that the resulting equivalent circuit, in the two above-mentioned cases, is a ferroresonant circuit consisting of a voltage source feeding a nonlinear inductance in series with a linear capacitor. As is shown later, severe and sustained ferroresonant overvoltages may appear between the faulted phases and ground. The transformer also would draw pulses of high current.

Because of the nonlinearity involved, mathematical formulation of the problem would be extremely tedious and generally not practical. However, for understanding the basic phenomenon of ferroresonance and the significance of the parameters, linear circuit theory is quite useful.

In Fig. 1, for one open phase, where switch SC-c is opened, the circuit can be reduced to a single-phase series *LC* circuit excited by a voltage source. The inductive and capacitive reactances of the resulting series *LC* circuit are respectively equal to $X_m/2$ (X_m is the per phase magnetizing reactance of the transformer at a voltage of 1 per unit) and X_{C0}. The excitation source voltage equals $-\frac{1}{2}V_{SC}$.

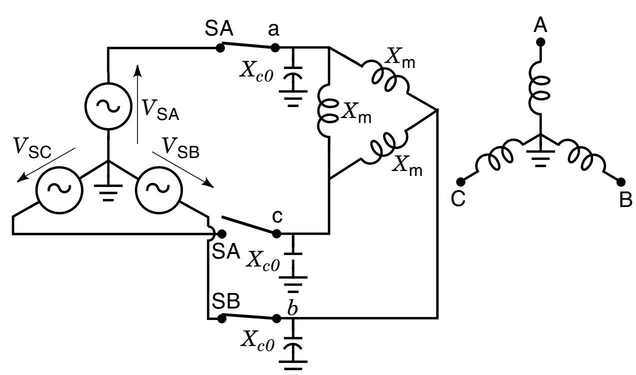

Figure 1. Schematic representation of a three-phase power transformer connection susceptible to ferroresonance. The primary side (low voltage), delta connected, is accidentally supplied by one or two phases. The secondary side (high voltage) is unloaded and wye-ground connected.

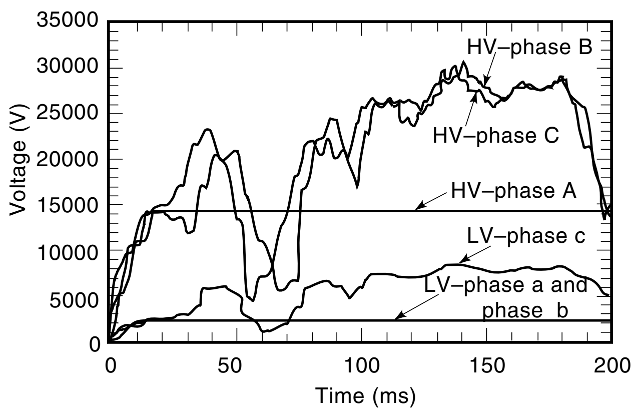

Figure 2. Time-domain representation of the transformer's primary and seconday *abc* rms voltages for one open phase (primary phase c is opened).

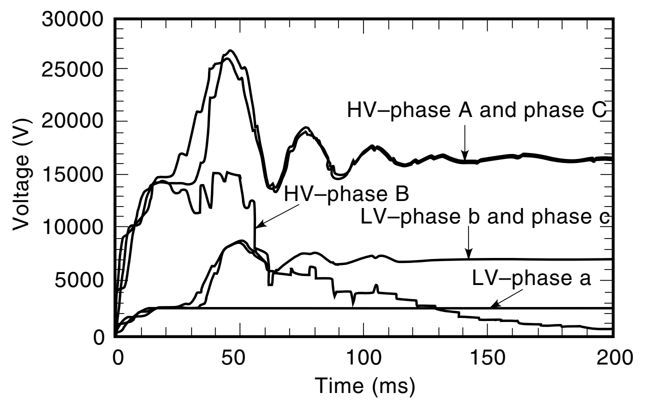

Figure 3. Time-domain representation of the transformer's primary and secondary *abc* rms voltages for two open phases (primary phases b and c are opened).

The resulting voltage value on the transformer side of the open phase is given by

$$V_c = V_{SC}\left(\frac{X_{C0}/X_m}{1-2(X_{C0}/X_m}\right) \tag{1}$$

One can see, from the above equation, that V_c becomes infinity when the ratio $(X_{C0}/X_m) = 0.5$. This ratio is also called the overvoltage factor. It is important to note that, in addition to the appearance of a severe overvoltage on the open conductor, phase reversal is also possible: When, for example, $(X_{C0}/X_m) = 2/3$, then, from Eq. (1), $V_c = -2V_{SC}$.

In the case of two open phases, where switches SC-c and SB-b are opened, the transformer is energized by a single-phase voltage source. As in the previous paragraph, the circuit of Fig. 1 can be reduced to a single-phase series *LC* circuit excited by a voltage source: V_{SA}. The inductive and capacitive reactances of the resulting series *LC* circuit are respectively equal to $X_m/2$ and $X_{C0}/2$. The resulting voltages on the transformer side of the open phases (phases b and c), V_b and V_c, are equal values and given by

$$V_b = V_c = V_{SA}\left(\frac{-(X_{C0}/X_m)}{1-(X_{C0}/X_m)}\right) \tag{2}$$

From Eq. (2), it is clear that V_b and V_c become infinity when $X_{C0} = X_m$.

Note that similar results can be obtained when considering a grounded capacitor bank with ungrounded wye-transformer or an ungrounded capacitor bank with a grounded wye-transformer.

So far, by using linear circuit theory, we have shown that, depending on the value of the overvoltage factor (X_{C0}/X_m), severe overvoltages may occur for conditions corresponding to one or two open phases, which could cause surge arrester failure on the transformer side and be dangerous for the insulation integrity of the transformer. In fact, the magnetizing characteristic of the transformer is a nonlinear function of the exciting current: its magnetizing reactance value changes with the degree of saturation. Hence, when the resulting overvoltages exceed the saturation voltage level of the transformer, its magnetizing reactance drops sharply. This causes the capacitor to discharge into it, thereby entering a ferroresonant mode.

The EMTP software package was used to investigate this phenomenon in the two above-mentioned cases (one and two open phases). The nonlinear magnetizing characteristic of the transformer, which is by far the most important parameter to be considered in the EMTP saturable transformer model, is modeled using the "TYPE-98" single-valued saturation curve model of a transformer (1). The simulation results are shown in Figs. 2 to 4.

Figure 2 shows the rms voltages of the three phases of the primary (i.e., low-voltage side: LV) and the secondary (i.e., high-voltage side: HV) of the transformer in the case of one open phase. One can see that severe overvoltages occur on the faulted phase of the transformer LV primary side (phase c) and on phases B and C of the transformer HV secondary. One can also notice that a high level of harmonics is generated.

Figure 3 shows the rms voltages of the three phases of the primary (LV) and the secondary (HV) of the transformer in the case of two open phases. As in the previous case, severe overvoltages result on the faulted phases of the transformer (LV-phase b and LV-phase c) and on the phases A and B of the transformer secondary phases. Figure 4 shows the line current of the transformer in the case of two open phases

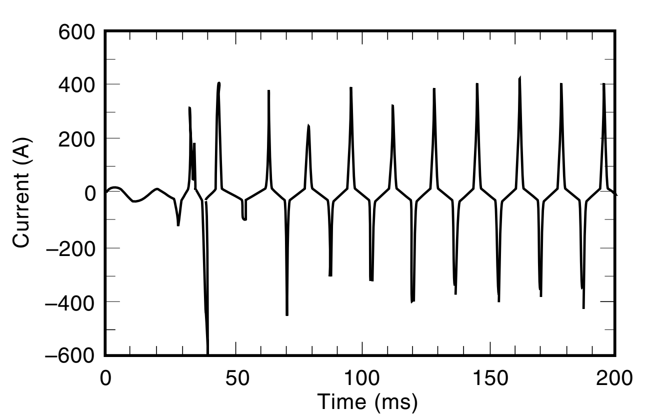

Figure 4. Time-domain representation of the transformer line current resulting from two open phases (primary phases b and c are opened).

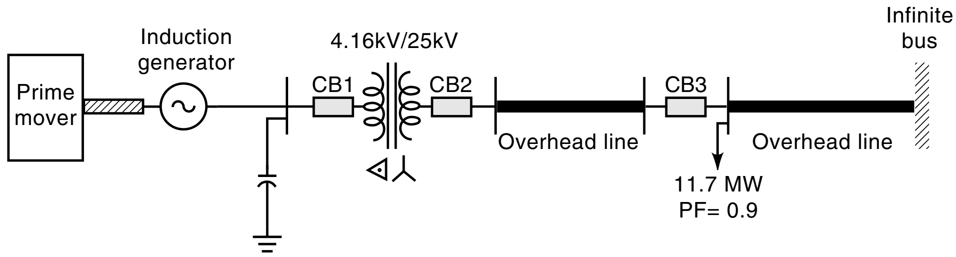

Figure 5. One-line diagram of a NUIG supplying a passive three-phase passive load via a power transformer and an overhead line. Part of the reactive power needed by the induction generator for magnetization is supplied by a three-phase capacitor bank connected to the stator of the machine.

(similar waveshape in the case of one open phase). It is mainly pulses of high current. It is clear that, depending on the duration of these pulses, the transformer may sustain thermal damages.

FERRORESONANCE CAUSED BY ISLANDING OF A NUIG FROM THE MAIN UTILITY

The integration of nonutility generators (NUG) into the main distribution system is an effective solution to increasing power needs, while taking into account economic and environmental factors. Because of their advantages compared to synchronous generators, namely, lower unit cost, reduced maintenance, and high reliability, induction generators are the most attractive candidates for small to medium NUG units. Figure 5 is a one-line diagram of a NUIG unit feeding a passive 11.7 MW load via a 4.16 kV/25 kV unit transformer and 25 kV overhead line. This particular transformer is in fact a commercially available distribution transformer used as a generator unit transformer for this application. The NUIG unit consists of a three-phase induction generator connected to the prime mover. A three-phase capacitor bank is connected to its terminals and serves as an additional reactive power source to establish the magnetic rotating field of the machine.

In this part of the article, we investigate the dynamical behaviour of the induction generator after its disconnection (islanding) from the main utility. The EMTP software package is used for this purpose. The induction generator is modeled using the universal machine UM-TYPE-4 (1).

Induction Generator Mathematical Model

The electrical equations (generator convention) of the induction generator, expressed in a dq reference frame rotating synchronously with the rotor, are as follows:

$$V_{ds} = -R_s I_{ds} - \frac{d\Psi_{ds}}{dt} - \omega_r \Psi_{qs} \tag{3}$$

$$V_{qs} = -R_s I_{qs} - \frac{d\Psi_{qs}}{dt} + \omega_r \Psi_{ds} \tag{4}$$

$$V_{dr} = -R_r I_{dr} - \frac{d\Psi_{dr}}{dt} \tag{5}$$

$$V_{qr} = -R_r I_{qr} - \frac{d\Psi_{qr}}{dt} \tag{6}$$

V_{ds}, I_{ds} and Ψ_{ds} are, respectively, the d components of the stator voltage, current, and flux linkage. V_{qs}, I_{qs} and Ψ_{qs} are, respectively, the q components of the stator voltage, current, and flux linkage.

V_{dr}, I_{dr} and Ψ_{dr} are, respectively, the d components of the rotor voltage, current, and flux linkage. V_{qr}, I_{qr}, and Ψ_{qr} are, respectively, the q components of the stator voltage, current, and flux linkage.

R_s, R_r, and ω_r are, respectively, the per phase stator resistance, the per phase rotor resistance, and the rotor electrical angular speed.

The currents are related to the flux linkage:

$$\Psi_{ds} = L_{\sigma ds} I_{ds} + \Psi_{dm} \tag{7}$$

$$\Psi_{qs} = L_{\sigma qs} I_{qs} + \Psi_{qm} \tag{8}$$

$$\Psi_{dr} = L_{\sigma dr} I_{dr} + \Psi_{dm} \tag{9}$$

$$\Psi_{qr} = L_{\sigma qr} I_{qr} + \Psi_{qm} \tag{10}$$

$L_{\sigma ds}$, $L_{\sigma dr}$, and Ψ_{dm} are, respectively, the d components of the stator leakage inductance, the rotor leakage inductance and the main flux. $L_{\sigma qs}$, $L_{\sigma qr}$, and Ψ_{qm} are, respectively, the q components of the stator leakage inductance, the rotor leakage inductance, and the main flux. The equation of motion is given

$$T_{\mathrm{m}} - (I_{qs}\Psi_{dm} - I_{ds}\Psi_{qm}) = \left(\frac{2J}{P}\right)\frac{d\omega_r}{dt} \tag{11}$$

T_{m}, J and P are, respectively, the mechanical torque, the total moment of inertia, and the number of poles.

Self-Excitation Phenomenon in an Induction Generator

It is a well-known fact that when an induction machine is driven by its prime mover above its synchronous speed (negative slip) while there is an external reactive power source connected to its terminals, it will generate electricity. This reactive power is required by the machine to establish its armature rotating magnetic field. The minimum amount of reactive power needed by the machine for magnetization, approximately 63% of the nominal reactive power of the machine, is given by

$$Q_{\mathrm{mag}} = \sqrt{3} U_n I_o \tag{12}$$

U_n and I_o are, respectively, the rated line-to-line voltage and the no-load armature current of the induction generator.

As shown in Fig. 5, in order to reduce the amount of reactive power supplied by the main grid, capacitor banks are connected to the induction generator's stator terminals. Many NUIG units use thyristor-controlled capacitors. However, if grid disconnection should occur (one of the three circuit breaker CB1, CB2, or CB3 is opened), the presence of these capacitors can be a serious hazard for both the equipment and

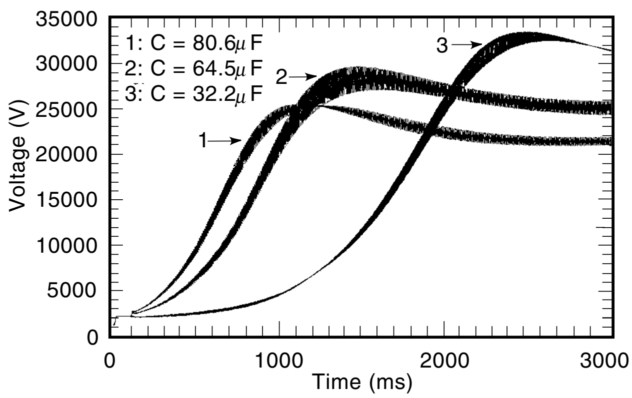

Figure 6. Time-domain representation of the stator rms voltage for three different capacitive compensation levels and resulting from the isolation of the nonutility induction generator from the power grid by opening circuit breaker CB1. The induction generator remains only loaded by the capacitor's bank.

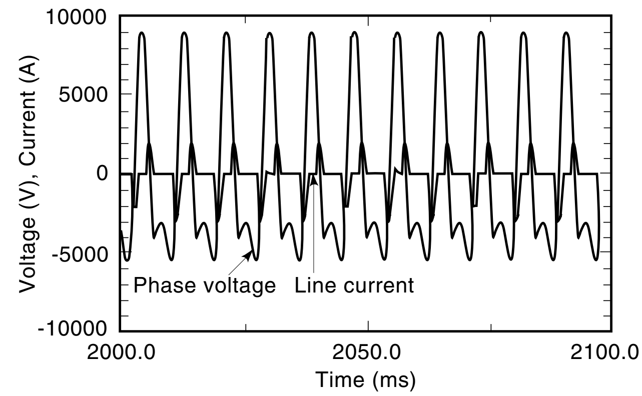

Figure 8. Time-domain representation (expanded time scale) of the stator voltage and the transformer primary line current resulting from the isolation of the NUIG from the power grid by opening circuit breaker CB3.

maintenance personnel. If, when disconnection occurs, the mechanical power is still applied by the prime mover and the capacitor value is sufficiently high to ensure self-excitation of the induction generator, high and destructive overvoltages will result at the machine terminals. According to the capacitive compensation level, the induction generator will either accelerate or slow down, respectively increasing or decreasing the armature frequency. A new equilibrium state, where the electromagnetic torque developed by the induction generator equals the mechanical torque applied by the prime mover, will be established. Ouhrouche et al. (8) have shown that the longer the time (a function of the capacitor's value) for the new equilibrium state to be established, the more severe are the electrical transients and the higher are the generated overvoltages at the machine terminals.

The following two islanding scenarios were investigated:

1. The circuit breaker CB1 of Fig. 5 is opened at t = 100 mS.
2. The circuit breaker CB3 of Fig. 5 is opened at t = 100 mS

Figure 6 shows, for the first scenario, the rms voltage at the machine terminals for three capacitive compensation levels: 125%, 100%, and 50% of the nominal reactive power of the induction generator. One can see that, after disconnection from the main utility, the steady state is reached at very high voltage levels: more than ten times the rated voltage of the machine.

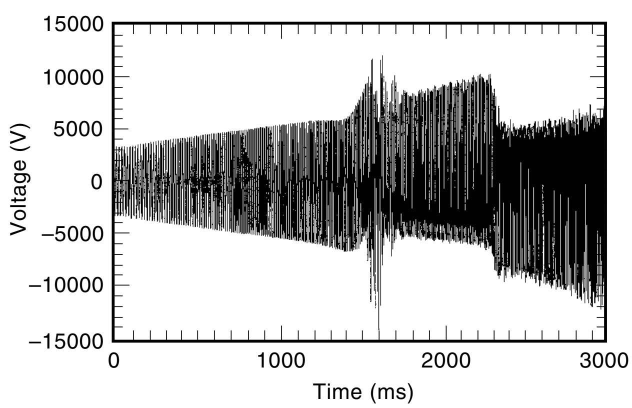

Figure 7. Time-domain representation of the stator voltage resulting from the isolation of the NUIG from the power grid by opening the circuit breaker CB3.

In the second scenario, the generator transformer is now involved. The generated overvoltages can deeply saturate the transformer which may trigger the occurrence of ferroresonance. Simulation results are shown in Figs. 7 and 8. Figure 7 shows the instantaneous generated phase voltage. Three regions can be identified: saturation, high saturation, and ferroresonance. When the generated voltage level exceeds the saturation level of the transformer (about 1.2 per unit), its magnetizing reactance decreases abruptly. Therefore the capacitors will rapidly discharge into it: Ferroresonance is definitely triggered. Figure 8 shows a zoom (in expanded time scale) of the instantaneous phase voltage and the line current absorbed by the transformer. The voltage waveshape is distorted which could cause the protective devices to not operate securely. Also, the transformer draws pulses of high current which could threaten the thermal capacity of the transformer.

CONCLUSION

In this article we have presented a study on the ferroresonance phenomenon in power distribution systems. Some circuit configurations which are more susceptible to experience ferroresonance are identified, in particular, distribution transformers with ungrounded primaries. The results show that severe and sustained ferroresonant overvoltages which are function of the overvoltage factor (X_{C0}/X_m) appear on the faulted phases of the transformer and the transformer draws pulses of high current. This could threaten insulation integrity and the thermal capacity of the transformer. In order to avoid ferroresonance, many researchers (5–7) have already suggested (1) the use of three-pole switching devices, (2) limiting primary cable length, (3) resistance grounding (5% of X_m) or solid grounding of all wye-delta transformers, (4) providing a secondary dummy load, and (5) limiting the voltage to ground on the open phase to 1.25 per unit.

The article also shows that ferroresonance is likely to occur in low- to medium-voltage systems involving NUIG units.

Here also the generated voltage to ground at the induction generator terminals must be limited to 1.25 times the nominal voltage of the machine.

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MOHAND A. OUHROUCHE
RICHARD J. MARCEAU
DAI X. DO
École Polytechnique de Montréal

FGCS. See FIFTH GENERATION SYSTEMS.
FIBER AMPLIFIERS. See OPTICAL AMPLIFIERS.
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