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Ferroresonance conditions in wind parks

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ABSTRACT

Wind parks are made up of a large number of saturable inductances (power transformers, inductive voltage transformers (IVTs)), as well as capacitors (cables, wind turbine harmonic filters, capacitor voltage transformers (CVTs), voltage grading capacitors in circuit-breakers). Therefore, they may present scenarios in which ferroresonance occurs. This paper presents the scenarios that can lead to ferroresonant circuits in doubly fed induction generator (DFIG) based wind parks. Ferroresonance conditions and their consequences are demonstrated by simulating the detailed model of the wind park in EMTP-RV. The wind park simulation model includes detailed models of wind turbines, medium voltage (MV) collector grid, high voltage/medium voltage (HV/MV) wind park substation, overvoltage, overcurrent and differential current protections, current transformers (CTs), IVTs and CVTs.

1. Introduction

Ferroresonance is an oscillatory phenomena caused by the interaction of energy exchanged between the nonlinear magnetizing inductances of the ferromagnetic cores and the system capacitances. The main feature of this phenomenon is the presence of at least two stable steady-state operating points for a particular range of circuit parameters: a ferroresonant operating point and a normal (non-ferroresonant) operating point. Transient disturbances or switching operations may initiate ferroresonance. The response can suddenly jump from one normal operating point (sinusoidal at the same frequency as the source) to another ferroresonant operating point characterized by high overvoltages and harmonic levels which may lead to excessive heating and insulation failure in transformers as well as significant disruptions in power system operation [1–4].

Although some literature on ferroresonance with wind generation is available [5,6]; none of them present a comprehensive demonstration of ferroresonance that occurs inside a large scale wind park.

This paper presents the scenarios that can lead to ferroresonant circuits in an actual doubly fed induction generator (DFIG) based wind park. Ferroresonance conditions and their consequences are demonstrated by simulating the detailed model of the wind park in EMTP-RV.

The first part of this paper presents the theoretical principles of ferroresonance. The second part presents the considered wind park and the electric configurations that can lead to ferroresonant circuits. The simulation results are presented in the last part.

2. Ferroresonance

In simple terms, ferroresonance can be described as a nonlinear oscillation resulting from the interaction between a nonlinear inductance and a capacitor. Like linear resonance, depending on the connection between the capacitance and the nonlinear inductance, ferroresonance may be series or parallel. This paper analyzes only the series ferroresonance shown in Fig. 1.

The graphical solution of the series resonant circuit is shown in Fig. 2 for the lossless case (i.e. $R = 0$). The intersection of "$U_S + U_C$" line with the nonlinear U_L (I) curve gives three possible operating points:

- Operating point (1): Non-ferroresonant stable operating point in which the circuit is working in an inductive mode, with lagging current and low voltages.
- Operating point (2): Ferroresonant stable operating point in which the circuit is working in a capacitive mode, with leading current and high voltages.
- Operating point (3): Unstable operating point.

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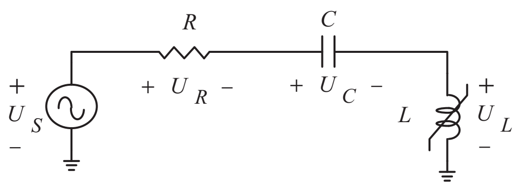

Fig. 1. Series ferroresonant circuit.

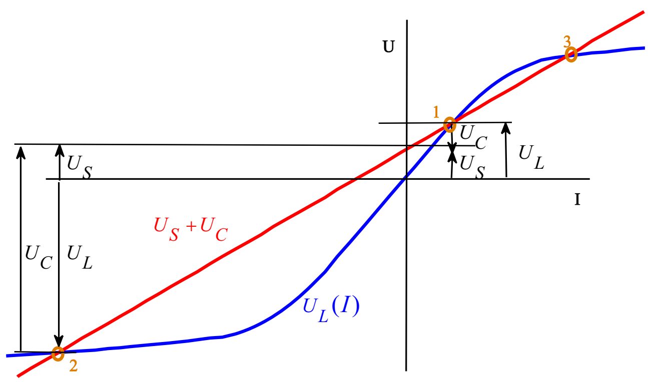

Fig. 2. Graphical solution of a series ferroresonant circuit ($R = 0$).

The nonlinear curves of iron cores are, in general, described as flux–current (λ–I) curves. However, the voltage–current (U–I) curve used in presented graphical solutions can be approximated as

$$U = \omega_0 \lambda = (2\pi f_0)\lambda \tag{1}$$

where f_0 is the power system frequency.

It should be noted that, the deep analysis of the circuit shown in Fig. 1 requires the solution of nonlinear differential equations. The presence of nonlinearity introduces harmonics in the voltage and current waveforms. However, in Fig. 2, the analysis of the circuit is simplified by limiting the calculations to the power frequency and steady state in order to provide a conceptual description of ferroresonance [7–9].

2.1. Effect of source voltage

The effect of the source voltage is illustrated in Fig. 3. As the source voltage is increased, the "$U_S + U_C$" line moves upwards. When the source voltage is higher than $U_{S\text{-}critical}$ ("$U_S + U_C$" line tangent to the nonlinear U_L (I) curve), there is no intersection in the first quadrant. In other words, the system solution is always a ferroresonant situation.

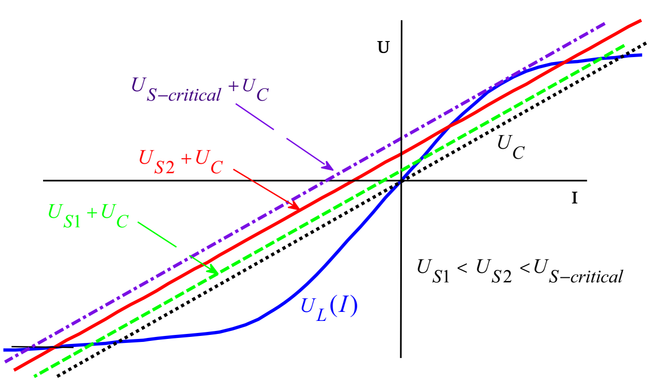

Fig. 3. Graphical solution illustrating the effect of source voltage.

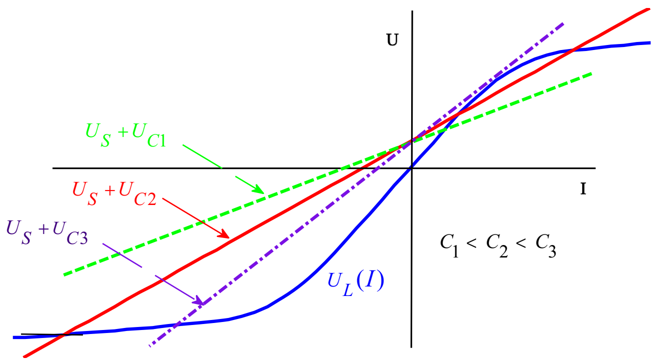

Fig. 4. Graphical solution illustrating the effect of circuit capacitance.

As seen from Fig. 3, the ferroresonant oscillations can be self-sustained when the circuit has no losses. In other words, removing voltage source may not result in the elimination of ferroresonance. The operating point simply slides to the right, but remains in the saturated region. In reality, ferroresonant oscillations cannot be self-sustained due to circuit losses.

2.2. Effect of circuit capacitance

The effect of the circuit capacitance is illustrated in Fig. 4. As the circuit capacitance is increased, the "$U_S + U_C$" line rotates clockwise, i.e. its slope decreases. As seen from Fig. 4, ferroresonant situation can appear for a wide range of capacitance values at a given frequency.

Fig. 5 illustrates the theoretical conditions to avoid periodic ferroresonance. It can be observed when [1]

$$\omega L_{sat} < \frac{1}{\omega C} < \omega L_{linear} \tag{2}$$

2.3. Effect of circuit losses

When the losses are considered, the equation describing the steady-state behaviour of the circuit shown in Fig. 1 can be written as

$$|U_L(I) - U_C| = \sqrt{U_S^2 - (RI)^2} \tag{3}$$

The graphical solution is shown in Fig. 6. For the low circuit resistance (R_2), there are three possible solutions. Solutions (2) and (3) in Fig. 6 correspond to the non-ferroresonant and the ferroresonant situations, respectively. As seen from Fig. 6, the multiplicity of solutions can disappear when the circuit losses increases.

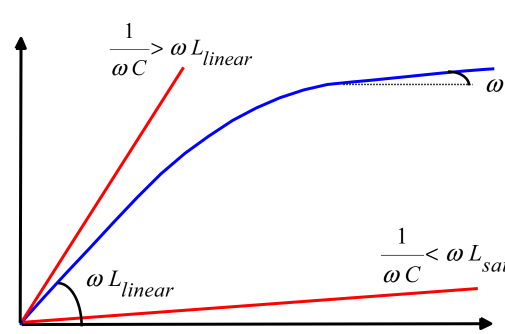

Fig. 5. Periodic ferroresonance conditions.