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Modelling and dynamic systems analysis of instability in a capacitor-coupled substation supplying an induction motor

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ABSTRACT

A capacitor-coupled substation (CCS) is a relatively inexpensive way of supplying power to communities living near high voltage power lines. However, when a CCS is used to supply a large induction motor (IM), self-excitation can occur, resulting in significant sub-synchronous voltage, current and speed oscillations. Useful insight can be obtained by analysing a CCS-induction motor (CCS-IM) system using analysis methods from control systems theory. In this paper, a dynamic model of self-excitation is formed and compensation techniques are analysed using Root Locus. The model is validated by comparing it with experimental results from a laboratory installation.

1. Introduction

A capacitor coupled substation (CCS), also known as a capacitive divider substation, is a relatively inexpensive way of supplying power to communities living near high voltage power lines because the cost of a capacitor bank and tuning reactor is substantially less than that of a conventional electromagnetic transformer. However, when a CCS is used to supply power to induction motors, particularly large induction motors with high inertia, instabilities may be experienced. These instabilities are typically characterized by sub-synchronous voltage, current and speed oscillations, and are termed “sub-synchronous resonance” (SSR).

A South African electricity utility installed a CCS to supply a 1.3 MVA induction motor (IM) in the vicinity of a 275 kV line. Severe voltage and current oscillations were experienced at low motor speeds (∼60% of operating speed) but the CCS worked well with a resistive load [1], indicating that instabilities were due to an interaction between the induction motor and the CCS.

Analysis of results from various technical reports of CCS-IM systems did not show the severe current spikes that occur twice every cycle that are typical signs of ferroresonance [2,3]. In the CCS installation supplying the 1.3 MW induction motor, a ferroresonance filter was unsuccessful in preventing SSR [3], while removing the filter did allow typical ferroresonance to occur. It is therefore unlikely that the SSR was caused or initiated by ferroresonance, which must not be overlooked when dealing with such systems and for which there are several tried and tested techniques for prevention [2,4,5].

This paper summarizes the CCS circuit, a previous analysis of self-excitation, the power injection remedy and an overview of the s-plane used in Root Locus methods. A dynamic model is developed, and Root Locus plots of the dynamic model are used to illustrate instability in various scenarios. A physical representation of the CCS-IM system was developed in the laboratory, and experimental results are compared with predictions from the dynamic model, leading to conclusions and recommendations.

The influence of the transmission network on the CCS-IM system was excluded in the modelling to allow a greater emphasis to be placed on the analysis of the SSR phenomenon.

2. Overview of key components of the problem

Three key concepts used in this paper are introduced in this section: the CCS parameters, IM self-excitation and a control systems approach.

2.1. Capacitor coupled substation

A CCS is a capacitor-divider, as shown in Fig. 1 with capacitors C1 and C2, across the incoming voltage (V_{in}) used to supply the desired tap-voltage (V_T), according to $V_T = V_{in}\, C1/(C1 + C2)$.

The CCS output voltage (V_{out}) is given by subtracting the voltage drop across the inductor (L). The inductor compensates for the reac-

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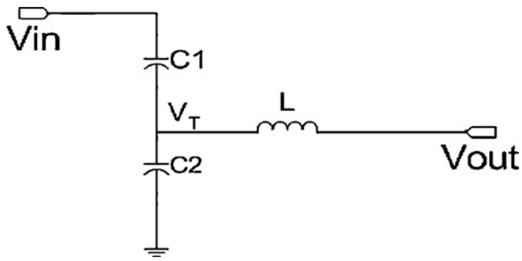

Fig. 1. Circuit diagram of a CCS.

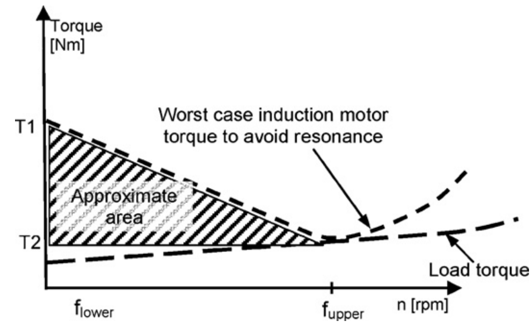

Fig. 3. Enlarged torque vs. speed curve of the region between the two resonant frequencies [3].

tive effect of the CCS capacitors, effectively tuning the supply to the nominal supply frequency. The calculation of the size of the inductor is based on the Thevénin equivalent capacitance C_{thev} = C1 + C2, and the nominal frequency, ω [rad/s], as given by $L = 1/(\omega^2 C_{thev})$.

2.2. Self-excitation

Wagner [6] studied self-excitation in the context of series capacitors being used to assist in the starting of IMs [7]. Currents can flow in a circuit in two ways: because of an external voltage applied to the circuit, or in accordance with the natural (resonant) frequency of the circuit. Normally, currents associated with the natural frequency of a circuit will eventually die down due to the resistance of the circuit, but in cases where there is little resistance to prohibit oscillations, they can become excessive. This means there will be less power and therefore less torque available for the appliance that is connected to the IM – see Fig. 2. When all of the torque available for the appliance connected to the shaft is used by the resonant circuit then sustained resonance occurs.

Expanding on Wagner's work, it is evident from Fig. 2 that in order for the system to avoid resonance, the IM torque curve must pass through the resonating region without intersecting the load torque curve. The worst-case scenario is shown in Fig. 3, which is a zoomed in region of Fig. 2, between the lower and upper resonant frequencies.

The shaded area of Fig. 3 is the approximate power required to prevent resonance, given by Eq. (1).

$$P = T\omega$$
$$P_{\text{compensator}} = \frac{(T_1 - T_2)}{2} 2\pi(f_{\text{upper}} - f_{\text{lower}}) \quad (1)$$

2.3. Control systems analysis method

Transfer functions are useful in representing dynamic systems by a set of linear differential equations. Once a transfer function has been formed, many tools can be used to analyse it. Root Locus is one of those tools [8]. The pole positions traced out by the Root Loci can be used to measure the degree of system stability and damping, as indicated by Fig. 4. Note that a Root Locus plot is symmetrical about the x-axis.

3. Dynamic model

Currents and voltages associated with a linear circuit have components that can be attributed either to the input stimulus (e.g. V_{in}) or to transients within the circuit itself [2,8,9]. The Root Locus analysis used here only examines those currents that arise due to the latter, in accordance with the natural frequencies of the circuit [6,10].

The Thevénin equivalent CCS circuit connected to the equivalent circuit of an induction motor was analysed. The parameters of the circuit analysed and used to build the laboratory model described later are shown in Fig. 5. The compensating inductance of Fig. 1 is not included here, but its effects are investigated later.

Using the method outlined by Braae et al. [9] and expanding on work done by Limebeer and Harley [10], a transfer function $g_2(s)$ relating the output, V_{out}, to the input, V_{in}, was found. This was adjusted in order to obtain an extended Root Locus plot; the relevant transfer function is shown in Appendix. It can be seen that the Root Locus gain is proportional to $1/q$, where q is the resonant slip instead of simply the slip, as we are dealing with system transients.

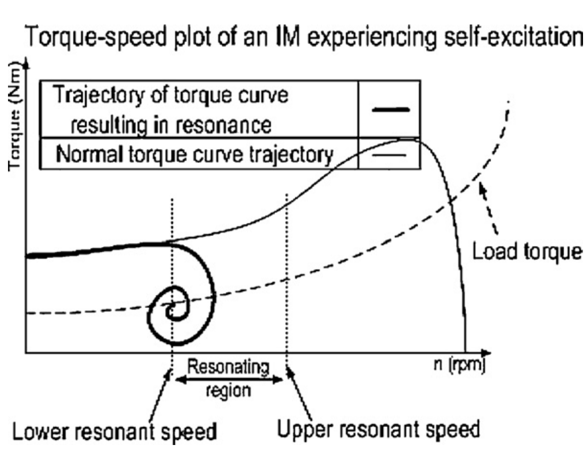

Fig. 2. Graph used to explain how resonance occurs, from a torque point of view [5].

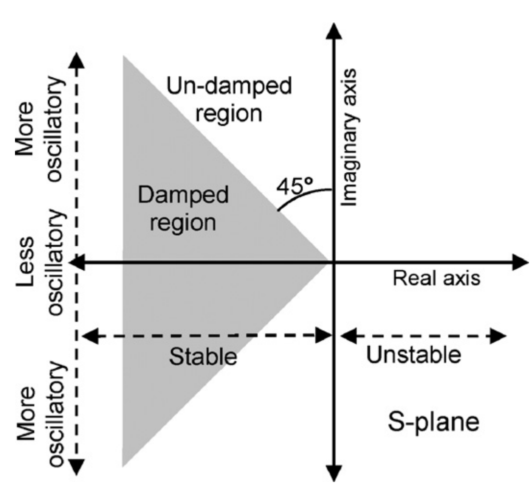

Fig. 4. Stability regions of a Root Locus [7].