Direct measurement of power angle of synchronous machines

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Abstract

In this paper, a novel method of measuring load angle of synchronous machines is presented. The load angle of the synchronous machine is directly related to the emf induced in the auxiliary winding of a load angle meter that is attached to the shaft of the main machine. The meter consists of a round rotor half and a salient pole half, which are coupled together and suitably interconnected. When the axis of the rotating stator excitation mmf coincides with the d-axis of the salient pole half of the device, the output voltage from its auxiliary winding will be zero and when it coincides with the q-axis, the induced emf will be a maximum. In general, the emf is proportional to the sine of the load angle.

1.0 Introduction

Practically the bulk of the electrical power fed into the power systems is generated in synchronous machines irrespective of the energy sources of the prime movers. In normal operation, these machines operate in synchronism i.e. they all generate at the same frequency and rotate at speeds which are simply related depending upon the number of poles of the individual machines i.e.

$$N_S = \frac{120f}{p} \quad \text{.........(1)}$$

When torque is applied to a machine connected to such a system, there is a movement of the rotor with respect to a continuously rotating reference. A synchronously rotating reference can be identified as the pole axes of an unloaded synchronous motor operating on the system. A synchronous machine running light will have its rotor pole axes coincident with the reference. When load torque is applied, the pole axes will move with respect to the reference and synchronous operation is continued with a steady angle between them. This angle is known as the rotor angle, power angle, torque angle or more commonly, the load angle. Load angle of a synchronous machine is validly defined as the electrical angle between a reference axis on the rotor of the generator and a set of synchronously rotating axes, obtained from the machine terminals or laboratory busbar.

If the rotor is driven ahead of the reference by applying shaft torque, the machine generates electric power and the load angle is taken as positive. If the shaft is loaded mechanically, electric power is absorbed and the rotor falls behind the reference with negative load angle. A change in shaft torque leads to temporary and oscillatory speed departures from the synchronous until synchronism is regained (Fig. 1). Similarly, the load angle also departs from the operating load angle δ_O and oscillates about a new position, such that when synchronism is regained, the machine continues to operate at a new load angle.

A plot of the power output (or shaft torque) against load angle δ, shows a steady-state characteristic of the form shown in Fig 2. Theoretically, maximum power according to equation (2) and depicted graphically in Fig 2 is developed at a load angle of 90°, however, this occurs in practice at an angle somewhat lower.

For a cylindrical rotor synchronous machine,

$$P_e = \frac{EV}{X_S} \sin\delta \qquad \ldots\ldots\ldots\ldots(2)$$

and for a salient pole machine,

$$P_e = \frac{EV}{X_S} \sin\delta + \frac{V^2}{2}\left(\frac{1}{X_Q} - \frac{1}{X_D}\right) \sin 2\delta \quad (3)$$

For load changes that take the machine close to peak output value, any further increase in shaft power will result in a decrease in electric power. The machine rotor will then accelerate if generating, decelerate if motoring, and synchronism will be lost i.e. instability results.

Synchronism can also be lost for a machine running below the stability limit if a sudden alteration in load causes load angle to exceed the angle for maximum power by too great a margin. This implies that the stability of a power system (i.e. continuous running of all the synchronous machines within it) is decided by the variations in load angle of the machine as the load is changed. The most serious changes are usually due to faults and the inevitable disturbances following switching action to clear these faults.

While accuracy is of the utmost importance in the measurement and synthesis of δ under steady-state conditions (it provides information on the output power) [9], speed of response is highly desired in the measurement of this important parameter of synchronous machines under transient conditions. Either way, δ is measured for the following reasons:

(a) It is useful in the prediction of operational impedances in the d- and q-axes.

(b) It provides a guide to the limits of stability of the system and assesses control strategies aimed at restoring synchronism.

(c) Rotor angle measurements within the appropriate bandwidth are also very useful in the observation of rotor torsional modes; and

(d) Finally, if a signal that has linear or near linear relationship with δ can be obtained from a synchronous machine, it will offer a most useful tool for feedback control mechanism applied to both the exciter and the governor to damp rotor torsional oscillations.

A number of full-scale tests have been performed on micro-machine models of synchronous machine. A micro-machine is a scaled physical model, which simulates the behaviour of large synchronous generators in the laboratory environment. Micro- machines are extremely used in universities and research and research laboratories to test novel instruments and control schemes. To this end, measurement of load angle over the years have been centred around four major classes:

(a) Comparison of the angular difference between the excitation voltage and the terminal voltage of the main machine under test [2,3], a method that gives accurate results so long as the synchronous machine whose load angle is desired is not connected to an infinite busbar. This is so because if the machine were to be so connected, the synchronous reactance of the local machine (from which the excitation voltage is synthesized) will be responding to fluctuations in the transmission system. Again in such synthetic methods, it is usually difficult to know the zero position of the load angle meter prior to test. For this reason, this method finds the majority of its applications in transient behaviour studies of synchronous machines under perturbed modes. Finally, these vector synthesis methods refer to δ as the angle between the excitation voltage E, and the terminal voltage V. This angle has to be redefined when the synchronous machine is of the reluctance type that operates without any form of dc excitation. It is defined, in this case, as the angle between the rotor d-axis and the axis of the rotating stator mmf.

(b) The second is the stroboscopic method first reported by Prescott and Connon in 1930 [4] and later in a more refined form by Powell and Harper [5] in which a gas discharge tube energized from a generator voltage transformer and arranged to shine directly on a disc (which is marked in degrees) is made to flash at frequencies related to that of the main flux wave. A change in load angle produces a corresponding rotation in the disc and just as in the synthetic method described above, is suitable for accurate measurements in local machines not connected to the infinite busbar. Fluctuations of the transmission system will obviously blur the image on the disc and the load angle can only be described as a value within a certain range. Nevertheless, researchers are still using this method as the reference from which every other measuring technique is assessed.

(c) The third and the most popular of all these methods is that of obtaining an electric signal, which is a function of the rotor angular position, and comparing it in phase with the generator terminal voltage. Different ways of obtaining the electric signal have been explored - the auxiliary commutator [8], electromagnetic systems employing a pick-up head close to the rotor to which is attached a permanent magnet [1], ac machines attached to the generator rotor shaft [9,10], and photoelectric systems employing alternate light and dark bands on the rotor [11,12]. In particular, the auxiliary commutator device gives direct readings, and can be used with machines having varying pole numbers. However, it is amenable to dc machine commutation limitations like brush wear and sparking. Two general shortcomings of the angular position methods are the amount of equipment needed to obtain a record of load angle; and that they all require film records of dots spaced at different intervals of times for a record of transient load angle to be obtained. The development and the processing of the film could be a lengthy process even though it might be desired that the operating engineer be immediately informed of the rotor behaviour as the local machine tends towards instability.

(d) The fourth class is the method of using micro-processor chips and additional circuitry configurations [6, 7] to measure load angle. These schemes though reported as different from the above [1-5, 8-11] are to a large extent dependent on them for signal sensing. The notable thing is that the scheme provides digital values of load angle, higher efficiency, light and compact construction and flexibility of control with low cost microprocessors. The overall idea is to make δ available as digital signals for ease of use in control studies and provide in-depth information on the behaviour of the machines under variable frequency conditions.

In the new device introduced shortly, a unique method of obtaining the electric signal is described and though the device is excited by the infinite busbar, fluctuations of the supply system has a minimal effect on the output of the device. This output (voltage) of the device, which is proportional to the loading of the synchronous machine, is proportional to sinδ and can be read directly, using voltmeters or CRO.

2.0 Description of the measuring device

The device is made up of two polyphase synchronous reluctance machines whose stators are identical, and wound in the same manner. One machine has a salient pole rotor and the other a cylindrical rotor. The two machines are mechanically coupled and the overall set coupled to the main synchronous machine under test. On the stator of each of the device machines, an identical set of auxiliary windings is installed in addition to the main windings, which are connected in series. The auxiliary windings are also connected in series but the coil sides are transposed between the two sections of the composite machines. The single-phase equivalent circuit of the coupled machine is shown in Fig. 3. The machines are such that the number of magnetic poles of the device must equal that of the synchronous machine, and that the direct axis reactance X_D, of the salient pole machine be equal to the synchronous reactance X_S of the cylindrical rotor machine. The later ensures, as will be seen later, that when the main machine under test is not loaded (i.e δ=0), the induced emf on each of the auxiliary windings of both machines are equal, and by virtue of their transposition cancel out giving a net emf of zero. This very coupled machine if built with the specifications of large synchronous reluctance machines is capable (with modifications of the auxiliary winding circuit) of generating bulk power at very good power factors [13]. Analysis performed in this regard infers that infinite output power is obtainable in theory.

3.0 Mmf and flux

Analysis of the coupled device is performed from the airgap permeance point of view on the assumptions that the airgap flux distribution is not affected by hysteresis and eddy current effects; there are no fringing effects; the slots do not introduce any harmonics and the airgap of both machines are small enough compared to the radius of the stator bore for a developed model of the machine to be used.

If an mmf $M\cos(\theta-\omega_o t)$ is established in both machines, the flux density distribution in the round rotor machine would be:

$$B_c = MP_c\cos(\theta-\omega_o t) \quad \ldots\ldots\ldots\ldots(4)$$

where P_c is the uniform permeance distribution per unit length of the round rotor machine. If the permeance distribution in the salient pole half of the device is:

$$P_s = P_o + P_1\cos2(\theta-\omega_o t-\delta) \quad \ldots\ldots\ldots\ldots(5)$$

(neglecting higher order harmonics), the flux density in the airgap would be:

$$B_s = P_o M\mathrm{Cos}(\theta-\omega_o t) + P_1/2\ M\cos(\theta-\omega_o t-2\delta) \ldots (6)$$

The net flux linking the auxiliary windings would be:

$B = B_c - B_s = MP_c\cos(\theta-\omega_o t)$

$-[P_o M\cos(\theta-\omega_o t) + P_1/2 M\cos(\theta-\omega_o t-2\delta)]$ (7)

When $\delta=0$,

$B = (P_c - P_o - P_1/2)M\cos(\theta-\omega_o t)$ …………(8)

When $\delta=\pi/2$,

$B = (P_c - P_o + P_1/2)M\cos(\theta-\omega_o t)$ ………(9)

At any other intermediate position, it will be:

$B = (P_c-P_o-P_1/2(\cos 2\delta - j\sin 2\delta)) * M\cos(\theta-\omega_o t)$. ………(10)

For the induced emf to be zero at no load, the net flux linking the auxiliary winding will be zero. Hence, from (8), it can be seen that:

$P_c - P_o - P_1/2 = 0$. ………(11)

The overall induced emf in one phase of the series connected but transposed auxiliary windings at any loading condition will be given therefore as:

$e = (P_c-P_o)(1-\cos 2\delta + j\sin 2\delta)M\sin\omega_o t$ ….(12)

Therefore, $e \propto (1-\cos 2\delta + j\sin 2\delta)\sin\omega_o t$ hence $e \propto \sin\delta$

From equation (12), a phasor diagram (Fig. 4) can be drawn. From the diagram, it is clear that:

$ED = j(P_c-P_o)\sin 2\delta$, $O'D = (P_c-P_o)\cos 2\delta$ and $OE = OO' - O'D + jED$.

Hence the vector being measured is

$e = OE = OC\sin\delta$. …………(13)

4.0 Measurement Technique

Fig. 5 shows the schematic diagram of the machine as it should be coupled to and fed from the generator terminals through a 3-φ transformer and a phase shifter (which could be a 3-φ induction generator). The phase is adjusted so that when the test machine is unloaded, the reading of the instrument voltmeters is zero. A phase shifter will not be required if it is possible to rotate the circumferential position of the meter such that the reading of the indicating voltmeters will be zero at no load. Once this position is obtained, the stator is secured firmly to the frame of the test machine. The terminals of three-phase output of the auxiliary windings (A, B and C) are connected to the indicating voltmeters through a three-phase rectifier.

In order to minimise the effect of the variation of the impedance of the primary windings of the meter with the load angle δ, it is fed through a balanced 3-φ resistors large enough that the current drawn remains substantially constant irrespective of the load angle.

5.0 Conclusions

The equipment described has been shown to have the capability of measuring the power output of the test synchronous machine [9] and the load angle of a synchronous machine as an angular position of the rotor of the main synchronous machine. The induced emf (which is proportional to sinδ) can, by microprocessor algorithm, be converted to δ before applying it to the voltmeters. The sinusoidal nature of the

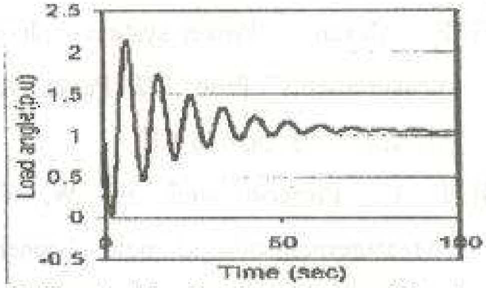

Fig. 1: Transient load angle variations following sudden increase in load.

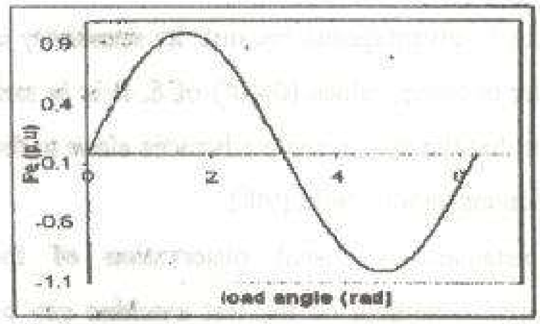

Fig. 2: Power angle curve for a synchronous machine

Fig.3: The per phase equivalent circuit of the measuring device

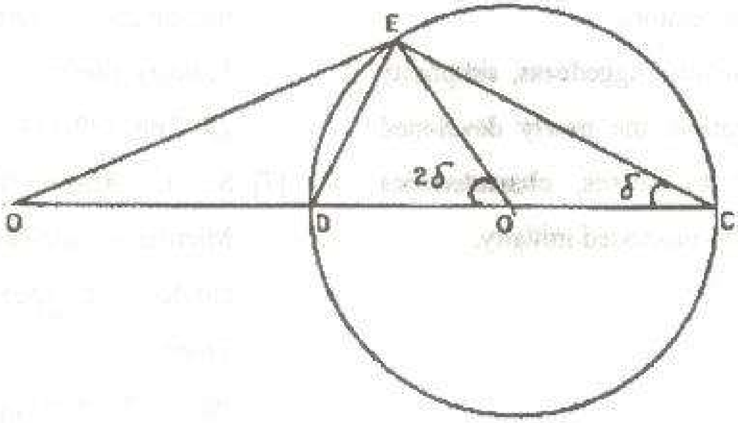

Fig. 4: The phasor diagram

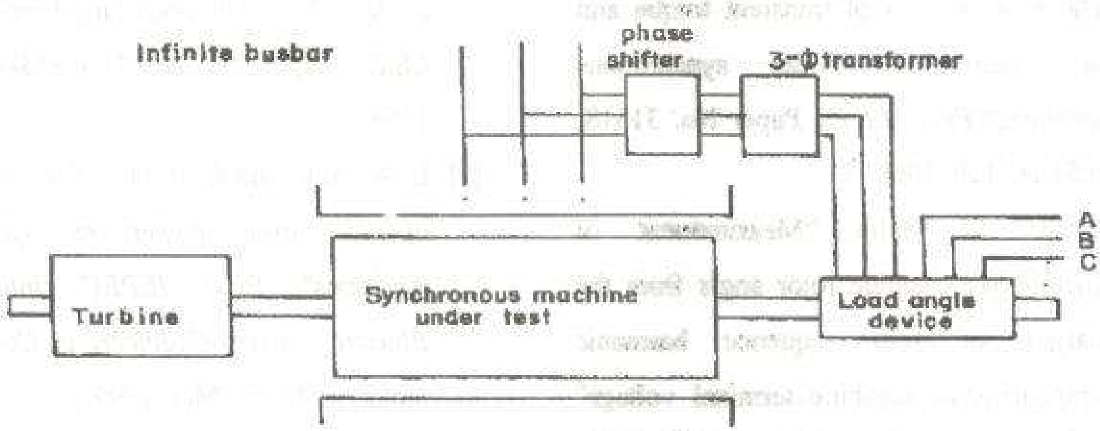

Fig. 5: Connection of the load angle meter to the synchronous machine

output is advantageous because its sensitivity is higher at lower values (0-40°) of δ. It is in rare cases that the power angle advances close to the maximum stability limit (90°).

Instantaneous visual observation of the transient behaviour of the test machine can be accomplished by applying the three phase rectified output to a cathode ray oscilloscope unlike other methods that requires that the film records of the machine behaviour be processed before it can be evaluated.

The output voltage of the new device can be directly applied to control the steam valves of the turbine driving the generator.

In terms of accuracy, ruggedness, simplicity and ease of application, the newly developed device has shown to posses, characteristics superior to the devices discussed initially.

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