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The Application Of Bond Graphs To Electrical Machinery And Power Engineering

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Several SESs have been designed according to the new LOPS method. The largest system is a 1.6kW peak system that has been in operation for two years. During this period the energy balance of the system was measured and registered daily. Comparison of the measured results to theoretical ones points out clearly that the newly proposed method is an efficient and economical tool for the design of autonomous (stand-alone) SESs.

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The bond graph technique, which as been related almost entirely to the field of mechanics, is a modeling procedure where emphasis is placed on the flow of power and energy in a system. Through specific digital simulation programs such as ENPORT IV and V and THTSIM the state space representation, associated output equations and system dynamic response are directly obtainable from the bond graphs. This approach has a great advantage where a complex system is composed of electrical, mechanical, thermal, hydraulic or pneumatic subsystems, such as would exist, for example; in a boiler, turbine, generator system together with its associated controls.

The purpose of this paper is three-fold: (1) to develop interest in the bond graph modeling technique in power engineering (2) to develop bond graph models for typical synchronous and induction machines which are not as well developed in the literature as are the graphs of mechnical components and (3) to complete some of the missing links in the development of bond graphs for electromechanical machines.

Standard well-known orthogonal axis transformations are used in the model development. The bond graphs thus developed from accurate mathematical relations can be easily integrated into other electrical or non-electrical systems through the power bonds of the graphs.

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Measurement of Vector Ratio in Three-Phase Transformers

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In three-phase transformers it is desirable to know the vector voltages on the secondary of the transformer relative to the primary vector voltages for balanced, sinusoidal three-phase voltage applied. In ANSI-C57.12.90-1980, Fig. 8 is given a method for qualitatively determining the phase relations for the standard connections. However, more general and accurate methods are desirable, especially for units with odd phase shifts, as for example phase angle regulators and rectifier transformers.

The method to be used here is based on the principle of superposition in linear circuits. For the purpose here, where a transformer is energized by several voltages, the output voltage on a desired terminal pair is the vector sum of the voltages on the pair due to each of the input voltages. When applying each input voltage, the terminals to which the other input voltages are applied are to be short circuited. For a transformer, this should be done in such a manner that negligible current is drawn by the transformer during the test. Also consideration needs to be given as to whether a particular terminal pair is suitable for measurement. The test connections or the transformer construction may be such that the terminal pair has very high regulation for the test method below, and measurements cannot be made.

The method here will assume the normal voltage applied to the transformer is balanced three-phase, three-wire voltage, or four-wire if desired for an input winding with a neutral available. The output for normal input is assumed to be balancd three-phase, three-wire voltage. The windings are to be symmetric on the three phases for general use of the method. Some transformers are meant to be energized four-wire and cannot be safely energized three-wire at full voltage due to oscillations of the neutral, over-stressing the insulation. However, these may be safely energized at reduced voltage, three-wire, for these tests. If only the three input line terminals and the three output line terminals are used, the criteria above for the transformer drawing negligible current and the terminal pair having low output impedence during the test are satisfied.

The test circuit is per Fig. 1 and the tests to be made are shown in Table I.

Although a three-phase source is shown, actually only single phase voltage is applied to the unit. The test is made with a conventional single phase ratio test set. The output voltage on P and Q is always either in or out of phase with the applied voltage. If the voltage is out of phase, interchange the LV leads from the test set and label the ratio as negative.

For simultaneous application of the voltages E_{AB} and E_{CB}, and letting $E_{CB} = E_{AB}\angle 60$, E_{PQ} is:

$$E_{PQ} = R_1 E_{AB} + R_2 E_{AB}\angle 60 \qquad (1)$$

The reference input voltage will be considered as $E_{AG} = (E_{AB}/\sqrt{3})\angle -30$. The vector ratio will be defined as,

$$R_{3\phi} = \frac{E_{PQ}}{E_{AG}} = \sqrt{3}(R_1\angle 30 + R_2\angle 90) \qquad (2)$$

The magnitude of the vector ratio will be called $\bar{R}_{3\phi}$ and the angle, Θ. These can be compared to these values from the theoretical voltage vector diagram for the transformer and they should agree satisfactorily.

From symmetrical component theory it can be shown that R_1 and R_2 are as follows.

$$R_1 = \tfrac{2}{3}\bar{R}_{3\phi}\cos\theta \qquad (3)$$

$$R_2 = \tfrac{2}{3}\bar{R}_{3\phi}\cos(\theta - 120) \qquad (4)$$

The above test method and formulas apply also to the unsymmetric winding arrangements of the open delta and T connections. This method is especially suitable for automated test methods where the calculations can be done by a computer.

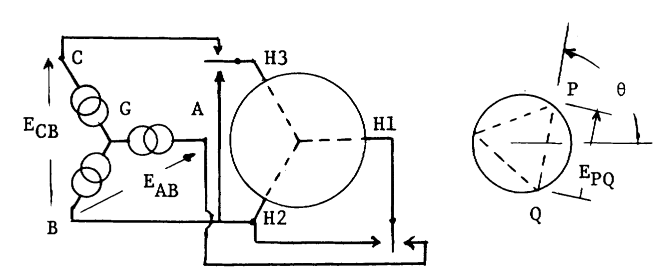

Fig. 1. Ratio Tests. The circles represent various winding connections.