Power System Balancers for an Induction Generator

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Abstract—**All power systems operate with some level of unbalance. A model for designing power balancers is presented. Induction generators are being used more extensively than in the past because of economics. Their use and a model are presented. Calculations and experimental data are used to demonstrate the feasibility of operating three-phase induction generators into a single-phase power system.**

INTRODUCTION

OPERATION of three-phase equipment on unbalanced power systems has long been an intriguing idea. Three-phase equipment is used since it can handle large quantities of power efficiently and is much less expensive than single-phase equipment of similar ratings. However, problems arise when this equipment is operated under serious conditions of unbalance. At a minimum, the effects generally are vibration problems, heat buildup, and shortened life. Because of these conditions it is desirable to have balanced systems.

In most cases the power company does an admirable job of providing the high-quality energy desired. Nevertheless, in many areas balanced three-phase power is not available, particularly in remote, rural areas. The power grid in these remote areas is as sparse as the population. In many cases the only utility power available is single-phase residential service. In a few areas, two-wire three-phase power systems exist; however, these systems are totally unbalanced. A third type of unbalanced power system is a three-phase system created from two or three independent single-phase sources.

Little was done to correct unbalanced power problems in the past. The problem persisted and the equipment performance suffered. Techniques now exist to relieve some of these problems. Interestingly, much of the theory has been available for years but has been developed in practical application only in recent years because of economic considerations.

The authors have been involved in using a variety of these techniques and procedures. However, their primary interest in this paper will be the presentation of operation of a three-phase induction generator on a single-phase power system. A single-phase power system is the limit of unbalance for operation of three-phase equipment. In addition, precisely the same technique is appropriate for balancing the load on a synchronous generator and for providing a balanced three-phase load to the power system with a large single-phase load. Only slight modifications are required to use the technique to balance three different line currents in a three-phase system.

INDUCTION GENERATORS

Historically, the term generator has implied a synchronous machine because of the overwhelming preponderance of this type of equipment. The term synchronous generator conjures ideas of complex equipment with tricky controls but yielding a quality power source. However, current interest for nonutility generation has tended toward induction machines because of their operating flexibility.

Induction machines as motors are very common among electrical energy users. The applicability of these machines as generators has been known since the late 1800's when Tesla [1] and Danielson [2] published their early research. Use as generators has been restricted because of their inability to generate and regulate voltage. Nailen [3] addresses many of the operational problems that have restricted the use of induction generators.

The interest in induction generators is keen because of the widespread familiarity with induction motors. There are large numbers of these machines available. They are easy to install and operate, and they are very price-competitive because of their commonness and utility. Large-scale government and private studies [4] have demonstrated the cost-effectiveness of these machines. Nailen [5] has illustrated the applicability of large-scale induction generators where stable power systems exist. Durham and Ramakumar [6] proposed the use of small-scale machines for cogeneration in remote areas.

The installation of an induction generator is the same as the installation of the machine as a motor. The device should be called a motor/generator since the only difference is the speed at which the shaft is driven.

One additional control device is required to protect a generator—a shaft overspeed control. Excessive excitation can cause the machine to "run away" or to have excessive no-load voltage. Although the controls are not particularly sophisticated, proper precautions should be used to protect for some of the unique characteristics of induction generators.

Induction generators are being applied in a variety of industrial applications. The size of induction generators in use ranges from small integral horsepower units to 15 000-hp

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machines. Operating voltage ranges are from common distribution system voltages of 480 V to medium-voltage applications of 13 000 V. The source drivers for the machines vary widely—from waste heat recovery in petroleum plants, paper mills, and cement plants to prime movers such as gas engines, aeroturbines, and hydroturbines. With any driver used, the machine must be connected to a power grid for reactive excitation and for a receptor of power.

Ideally, a power system is a perfectly balanced, symmetrical, infinite bus. All studies found in the literature on application of induction generators make this assumption, but there are vast areas for the potential use of induction generators where this is not true. These are often the areas where inexpensive or otherwise desirable sources of energy are available. The high plains of western Oklahoma and Texas provide one of the richest sources of wind energy in the country. This area is also rich in natural gas, which is often in relatively small, unmarketable quantities as a byproduct of oil production. It is desirable to use these energy sources to generate electric power since it is one of the easiest energy forms to transport.

The induction generators in this service would be relatively small—less than 100 hp—compared to most induction generator applications. Nevertheless, this size is significantly larger than available single-phase motors. Furthermore, the cost of three-phase motors over 5 hp is substantially less than an equivalent-size single-phase motor. For these reasons it would be desirable to use a three-phase motor as an induction generator on an unbalanced (single-phase) system, if possible.

Because the induction generator is the same machine as a motor, many things are known about the equipment and its performance. Some of the more readily available information are the equivalent circuit and performance characteristics, including the impact of speed, current, power, and torque.

The per-phase equivalent circuit of the induction machine shown in Fig. 1 has been used extensively for analysis. Three of these circuits are used to represent the three phases of the machine.

Since the machine has an external driver, it is obvious the generator will continue to operate if one phase is open on the power system. From observation it is apparent the generator will not stall if lightly loaded and will be protected by overload relays if heavily loaded. Although these observations can be made, it is also apparent that the performance of the machine will suffer from the unbalanced operation on a single-phase system.

A review of the available literature on industrial cogeneration, induction generators, and unbalanced power system analysis illustrates the sparseness of information on operation of three-phase induction machines in very small installations. Moreover, literature on balancing such systems is virtually nonexistent.

There are several potential problem areas that must be solved in these type systems. Ultimately, on practical systems an engine or other source will be used to drive a three-phase induction generator. Starting and, for that matter, running a three-phase motor on a single-phase system cannot be done without additional equipment. Typically for motors with ratings less than 50 hp, phase converters have been used. These are either static devices or modified rotating machines.

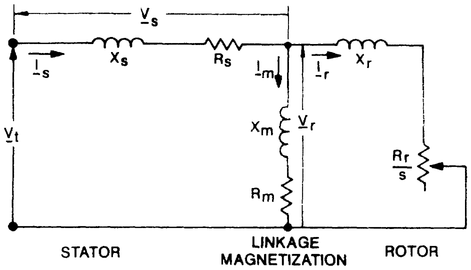


Fig. 1.

The induction machine will generate real power, but magnetizing current must be supplied from an external source. The power system itself or capacitors at the machine terminals can be used to supply this excitation. However, too much capacitance will overexcite the machine and may cause it to speed up or to generate excessive voltage.

Another area that must be evaluated is the amount of loading that can be placed on an unbalanced three-phase machine. For a constant load, as the current is reduced in one phase, the currents in the other two phases increase. These currents must be limited to reduce the copper losses and overheating of the machine.

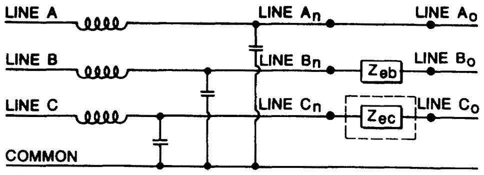
From these observations it is assumed the machine performance on an unbalanced system is probably not acceptable. Therefore a method of balancing the system is desirable. Several constraints should be placed on such a balancer. The major one is that resistive components should not be added since they consume real power. A secondary consideration is that passive devices are preferred since the equipment would be economical and simple to install and operate.

LINE BALANCERS

This section presents an idealized representation of a power system balancer for steady-state analysis. It also includes discussion on how balancers can be used to resolve unbalanced conditions in a power system. The balancer presented is generalized to permit it to be used to define any segment of a power system. Since each phase is modeled individually, unbalanced conditions can be resolved on a per-phase basis. As an illustration, by adding appropriate impedances in two lines, the currents in those lines can be forced to become equal to the current in the third phase. For this discussion, balanced conditions are defined as equal current magnitudes with 120° phase difference between any two phases.

The circuit elements of a line balancer can be calculated from the balancer model shown in Fig. 2. The model is defined by setting the output side to the existing line conditions and the input side to the line condition to be achieved after balancing. If the internal impedances calculated from the model are added to the line, the line should be balanced as desired.

Obtaining single-phase power from a three-phase source is commonly done by connecting the single-phase load across two lines as shown in Fig. 3. Although this is adequate for the load, it places an unbalance on the source, since one phase has



THREE PHASE LINE BALANCING BY IMPEDANCE

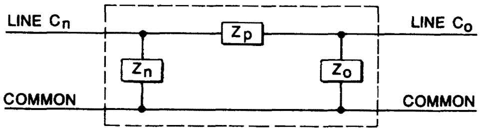
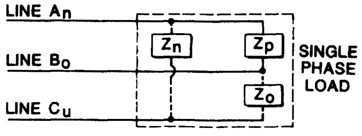
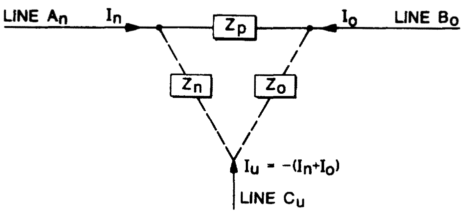


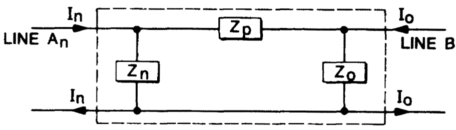
Fig. 2.



THREE PHASE FROM ONE PHASE LINE



IMPEDANCES TO CREATE THIRD LINE



BALANCER MODEL TO CREATE THIRD PHASE

Fig. 3.

no load. The balancer can be used to determine the circuit elements needed to create the third phase as shown by the dashed lines in the figure.

The previous paragraph describes a balancer for a single-phase load on a three-phase source. The same analogy applies for obtaining three-phase power from a single-phase line. By the use of the balancer model, the elements needed to create a third line necessary for a three-phase system can be designed. The currents on all three lines will be equal in magnitude and separated by 120° in phase.

Three different types of line unbalance have been described. These are unequal three-phase line currents, large single-phase load on a three-phase system, and three-phase load on a single-phase system. The technique developed provides a practical method of resolving any of these or other types of line unbalance.

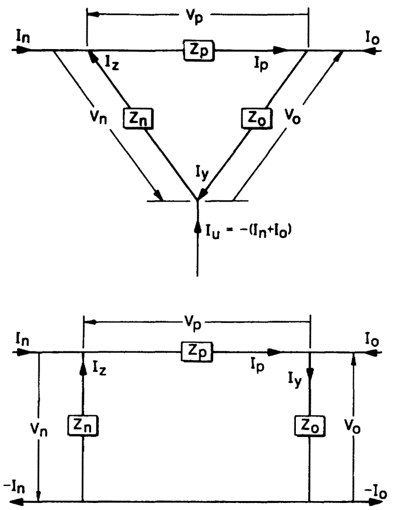


Fig. 4.

BALANCER MODELS

For operation of a three-phase induction generator on a power system, at least two basic requirements exist. The machine stator currents must be reasonably balanced or the machine will not operate effectively. The second but more critical item is that the induction generator supplies only real power to the system, but the machine requires reactive (lagging) power for excitation. This must be supplied by parallel synchronous generators and/or by capacitors on the line.

The solution to the problem of finding the network elements needed to satisfy both these conditions has traditionally been tedious or nonexistent. The use of the balancer model presented here has reduced this to a very practical problem. For balancing three-phase lines, one balancing element is required for each line. The model represents the line relative to a common or ground. This is a typical representation of electrical energy systems whether a three-wire ungrounded or a four-wire grounded system is considered. The current in one phase affects the currents in the other phases. Therefore, isolation of phases for analysis is accomplished by using superposition. This is a common practice, but it is usually assumed that the phases are identical and balanced.

The balancer models a segment of line while the input and output terminals are isolated from the line. Therefore, superposition can still be used. This technique is ideal for unbalanced analysis because the output is defined by a black-box network operating single-phase on the input. Even with unbalance caused by an open phase, the model will still describe the system. Only the input and output line parameters are required to define the balancer. The internal connections of the network between the terminals are determined from these external parameters.

Fig. 4 illustrates the parameters of the model and the sign conventions used. The direction conventions are made for a three-phase system. The general solution equations are then developed from Ohm's law and the power equation, both of which have three parameters—voltage and current with either impedance or power. Hence, using any two of these parameters will completely define an element in the balancer. Additionally, all these parameters are complex variables, which must be represented by their real and imaginary components or by their magnitude and phase.

EXAMPLE CALCULATIONS

For a balanced system, the line-to-line voltages must have the same magnitude. These voltages are determined by the power system to which the equipment is connected. For the single-phase load, the voltage across the load and current through the load can be measured. As noted previously, this data provides all the information necessary to balance the load on a three-phase system:

$$V_p = 100\,V \qquad a_p = 0^\circ$$

$$I_p = 17.3A \qquad b_p = 0^\circ.$$

To effectively solve the problem, the load must be converted to a resistance that represents real power flow. Even if the load is inductive, capacitance can be shunted across it to achieve an equivalent resistive load (unity power factor).

For a balanced three-phase system, the other two line voltages are required to be equal in magnitude to the single-phase load voltage. However, they must be separated by 120°:

$$V_n = 100\,V \qquad a_n = 120^\circ$$

$$V_o = 100\,V \qquad a_o = 120^\circ.$$

Since three lines will share the current through the load, each of the line currents are equal to the load current divided by 1.732. The three-phase line currents are shifted in phase from the load current:

$$I_n = 10A \qquad b_n = -30^\circ$$

$$I_o = 10A \qquad b_o = 90^\circ$$

$$I_u = 10A \qquad b_u = -150^\circ.$$

The power at the balancer terminals can now be calculated from this measured and defined data:

$$S_n = V_n I_n$$

$$= (100)(10) = 1000\ VA$$

$$c_n = a_n - b_n + 180$$

$$= 120 + 30 + 180 = 330^\circ$$

$$P_n = S_n \cos(c_n)$$

$$= 1000 \cos(330) = 866\ \mathrm{W}$$

$$Q_n = S_n \sin(c_n)$$

$$= 1000 \sin(330) = -500\ \mathrm{vars}$$

$$P_o = V_o I_o \cos(a_o - b_o)$$

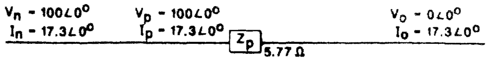
$$= (100)(10) \cos(-120 - 90)$$

$$= -866\ \mathrm{W}$$

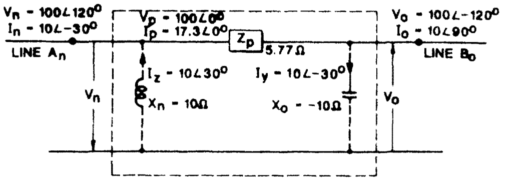
$$Q_o = V_o I_o \sin(a_o - b_o)$$

$$= (100)(10) \sin(-120 - 90)$$

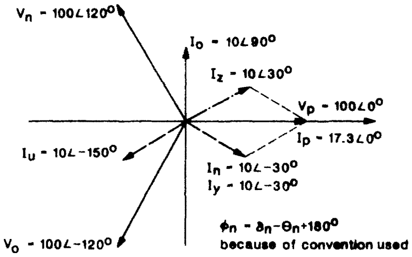
$$= -500\ \mathrm{vars}.$$



SINGLE-PHASE LINE



SINGLE-PHASE TO THREE-PHASE BALANCER



PHASOR DIAGRAM

Fig. 5.

With all the terminal values of power, current, and voltage established, the impedance necessary to balance the load can be calculated. The equivalent single-phase load-impedance value can be found from the load current and voltage, even though it is not an added impedance of the balancer. Since these were forced to real values, the load impedance does not have a reactive component:

$$X_p = 0.$$

Then the equivalent resistance is calculated:

$$R_p = \frac{V_n^2 + V_n V_o \cos(a_o - a_n)}{P_n}$$

$$R_p = \frac{(100)^2 - 5000}{866} = 5.77\ \Omega.$$

The shunt reactances are the impedance elements necessary to balance the load. Their values can be similarly calculated:

$$X_n = 10\ \Omega$$

$$X_o = -10\ \Omega.$$

This provides all the impedance values necessary to balance the single-phase load. The shunt impedances are equal in magnitude, but one is purely inductive and the other is purely capactive. These are illustrated in Fig. 5.

EXPERIMENTAL PERFORMANCE

Actual designs and experiments consisted of two parts: measurement of conditions on the generator with one line disconnected and balancing the single-phase to three-phase.

The first part is to measure the performance parameters of the machine with line C disconnected. This is the worst case of unbalance that can exist. The two remaining lines constitute a

TABLE I
MACHINE PERFORMANCE WITH ONE PHASE REMOVED

Case r/min	Torque *In-Lb*	V L-L *Vab*	*Vbc*	*Vca*	Angle (*Va* = ref) *Vbo*	*Vco*	Line amps *Ia*	*Ib*	*Ic*
1220	−50	214	175	206	−120.9	0	10.0	10.0	0
1230	−85	214	171	214	−120.4	0	11.9	11.9	0

TABLE II
MACHINE PERFORMANCE WITH CREATED PHASE

Case r/min	Torque *In-Lb*	V L-L *Vab*	*Vbc*	*Vca*	Angle (*Va* = ref) *Vbo*	*Vco*	Line amps *Ia*	*Ib*	*Ic*
1220	−51	219	234	192	−119.8	100.4	6.7	3.3	7.3
1247	−153	219	219	215	−119.3	116.8	6.6	6.6	7.3

single-phase condition. Even with one line removed, line-to-line voltage continues to exist across these terminals. However, the voltages are grossly unbalanced as shown in Table I.

Data samples generally cannot be taken at many different shaft speeds. Since line currents are excessive, the machine will overheat and vibration/noise problems will be encounterd.

The machine used as a generator for this analysis is a 1200 r/min, NEMA-D motor. The full-load speed when operating as a generator was approximately 1245 r/min. The full-load current was 9.4 A without power-factor correction. With power-factor connection, full load was achieved at approximately 7.3 A. The results of balancing the load were very good. As stated previously, line *C* was removed from the generator to cause a single-phasing condition. The third line was then created by a balancer.

To design a balancer for this machine, the line currents were required to be equal. A nominal value of 7.3 A was used to represent near full load on the generator at unity power factor. The currents through the shunt impedances of the balancer were equal to the line currents. The current through the single-phase line equivalent (series element) was 1.732 times the line currents. The impedance magnitudes necessary to create the three-phase balancer were 1.732 times the single-phase line equivalent impedance. The shunt impedance magnitudes required were 29.7 Ω.

These impedances were added to the terminals of the induction machine to recreate the line *C*. The results are shown in Table II.

For the three-phase generator, a current of 7.3 A was maintained on the created line *C* regardless of load. This was exactly as predicted. The created line will provide a fixed current for a given set of balancing reactances. The speed was then adjusted to change the ouput of the induction generator. Shaft speed for the induction generator controls the real power output. The adjustment of the speed and the resulting load can be used to achieve near complete balance of line currents for the selected values of balancer circuit impedances. The values will change slightly as the machine load changes.

Several observations from Fig. 6 are appropriate. The created line current is constant and is independent of speed or load. If the generator is operated at speeds near or slightly above where the output current matches the created line current, then balance is virtually complete. If the balancer is designed for full-load conditions, the line currents to the two existing power lines will decrease then increase from no load to full load.

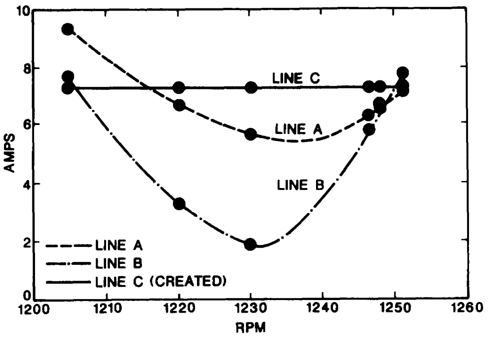


Fig. 6.

Two precautions should be noted and appropriate protection provided. The capacitors connected to the machine cause overexcitation leading to high voltage if the load is removed while the generator is being driven. A more serious problem to be avoided is the removal of the load with the created line *C* connected to the generator. Without the load a series-resonant network is present (the inductance and capacitance used to create the third phase) in which the voltages across the capacitor or inductor could reach dangerously high values. To avoid damage to the balancer components, some means of overvoltage protection must be provided if the voltage exceeds a preset value.

CONCLUSION

It is desirable to operate three-phase synchronous and induction machines, whether generators or motors, on a balanced system. However, in some cases the three-phase generator may only have a single-phase load or may be operating into a single-phase line. Alternately a three-phase line supplying a motor may be sufficiently unbalanced to create problems. Both of these extreme conditions and virtually any other unbalance in between can be resolved using line balancers designed according to the discussion presented in this paper.

Fascinatingly the balancing equipment uses only reactance inductors and capacitors. Therefore, real power consumption and associated costs are not significant. Incremental energy is not required. Moreover, no rotating or moving parts are required, so maintenance problems are minimal.

Balancers have been built and are operating for static single-phase loads up to 2 MW. Units for balancing three-phase currents in dynamic motor loads have been applied to several hundred horsepower. Units for induction generators have been used only experimentally in sizes up to 5 hp.

NOMENCLATURE

a_n, a_o, a_u	Phase voltage angle.
a_p	Voltage angle across equivalent load.
b_n, b_o, b_u	Line current angle.
b_p	Current angle through equivlant load.
c_n	Power-factor angle on input.
I_n, I_o, I_u	Line current magnitude.
I_p	Current through equivalent load.
P_n, P_o	Real power at balancer terminals.
Q_n, Q_o	Reactive power at balancer terminals.
R_p	Equivalent load (series) resistance.
S_n	Complex power input to balancer.
V_n, V_o	Phase voltage angle.
V_p	Voltage magnitude across load.
X_n, X_o	Shunt balancing reactance.
X_p	Equivalent load (series) reactance.

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