VOLTAGE REGULATOR AND PARALLEL OPERATION

Generator sets are operated in parallel to improve fuel economy and reliability of the power supply. Economy is improved with multiple paralleled generators by selecting only sufficient generators to carry the load demand at any given time. By operating each generator near its full capacity, fuel is utilized efficiently.

Power system reliability is improved by availability of generators not in use as backup for units on line. In addition, protective systems can be designed to detect a faulty element and isolate it from the healthy part while maintaining power to the remaining system. With multiple generators carrying the load, a generator that develops a problem can be shut down, allowing the remaining generators to carry the load.

Because of advantages of parallel operation, multiple generator installation has become common in applications for standby and prime power, portable and stationary power, commercial and military power; and they continue to grow.

Operating generators in parallel required attention to the two control systems of the generator set - the voltage regulator and the speed governor. This discussion is limited to the control of the voltage regulator.

PARALLEL OPERATION AND THE VOLTAGE REGULATOR

An example to illustrate the effect of the voltage regulator on the generator system can be seen using two batteries and a load. In Figure 1, two batteries with voltages *exactly* equal (open circuit) could divide load equally, with each battery pulling its share. If the two voltages are not exactly equal, the load will not be shared equally, and the benefit of two batteries will be lost.

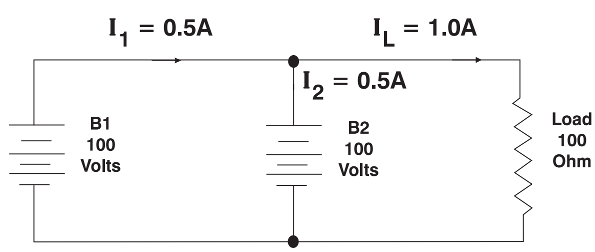


Figure 1: Paralleled Batteries - Equal Voltage

Further, the load division is very sensitive to voltage unbalance. In Figure 2, the battery with an output voltage of 102 (B2) will determine the load voltage, and the load sees a proportionally higher current. Battery B1 is being charged by B2 at a 5 ampere rate because its terminal voltage is lower. This charging current is obviously not proportional to the voltage level and results in a load current on B2 in excess of 6 Amperes.

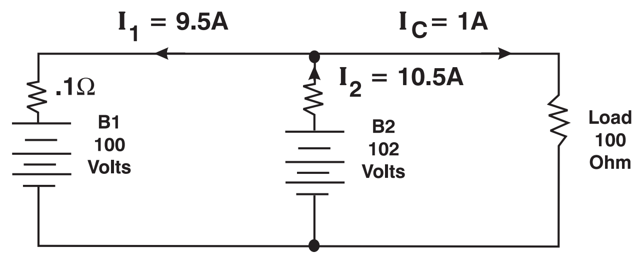


Figure 2: Paralleled Batteries - Unequal Voltage

In Figure 3, B1 is higher in voltage than B2 by 2 volts, causing B1 to supply the load and charge B2 for a total load current of 6 Amperes.

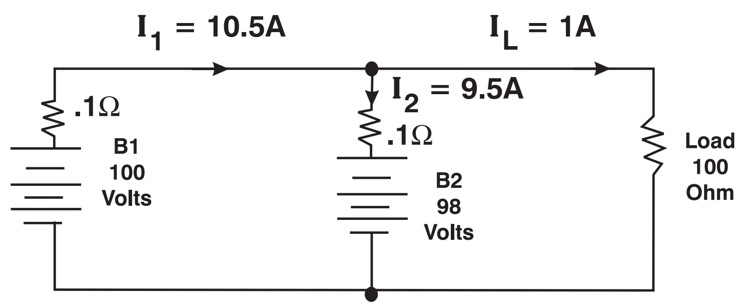


Figure 3: Paralleled Batteries - Unequal Voltage

Please note that the voltage referred to in the diagrams is the open-circuit voltage. As soon as the batteries are paralleled, the voltage at the terminals of the batteries becomes identical.

Two generators operating in parallel to supply a common load operate in a similar manner. If voltage (open-circuit) is exactly the same on both generators, they will divide the load equally between them. See Figure 4. Any small difference between generator voltages will result in unbalanced load division (Figure 5) or, in the extreme, circulating current (Figure 6).

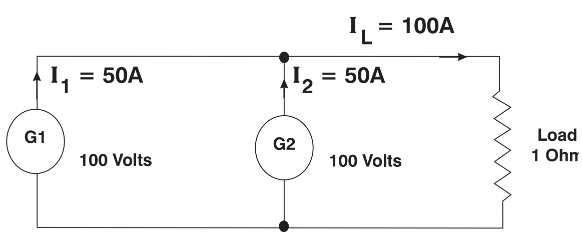


Figure 4: Paralleled Generators - Balanced Voltage

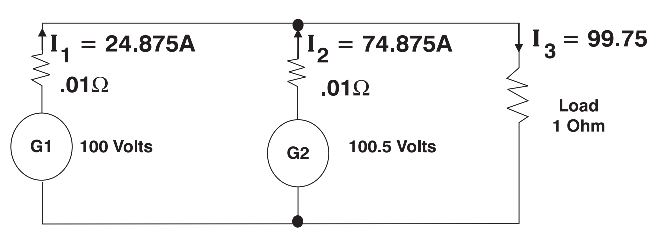


Figure 5: Paralleled Generators - Voltage Unbalanced

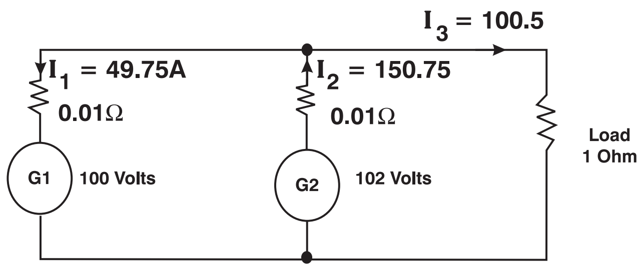


Figure 6: Paralleled Generators - Voltage Unbalanced

In practice, the precise matching of voltages is not possible. Some means must be provided to make load sharing between paralleled generators simple to control.

Because circulating current or load unbalance described above is the result of voltage mismatch, you might look to the voltage regulator for some help. The regulator can provide this help using paralleling compensation circuits called reactive droop compensation or reactive crosscurrent compensation. Both types will be described in detail in later papers.

The principle of operation of the reactive droop circuit, which is the simplest and most commonly used circuit, can be described by the curve in Figure 7.

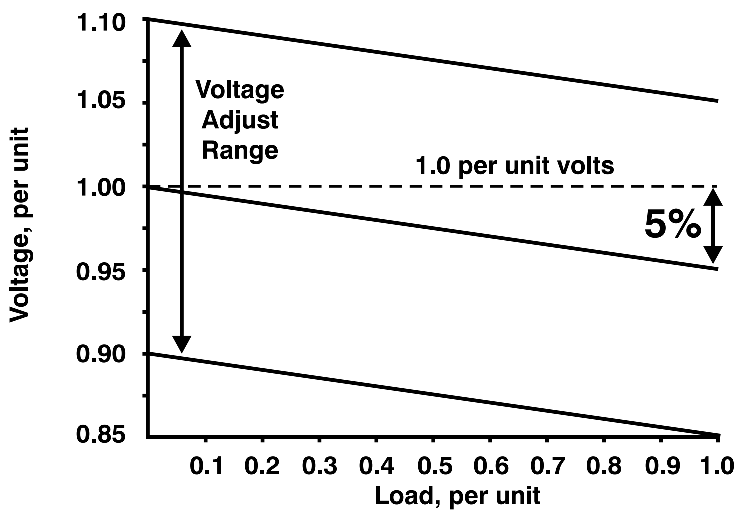


Figure 7: Reactive Droop Curves

Using a regulator designed to maintain precise voltage regulation, a circuit is added that accepts a current signal from the generator's output. This current signal is combined with the generator's sensing voltage signal to develop a vector summed voltage proportional to reactive load.

For example, if voltage decreases from 480 volts down to 458 voltage from no load to rated reactive (kvar) load, the voltage droop is -4.3% droop. If two generators are operated in parallel, with their droop curves set the same and their voltage setpoints adjusted to proportionally share the reactive load, any unbalance that would increase the load on one machine and decrease the load on the other would cause the droop circuits to change the voltage setpoints in a direction to bring the load back into balance. With droop compensation, the bus voltage will droop with changing reactive load.

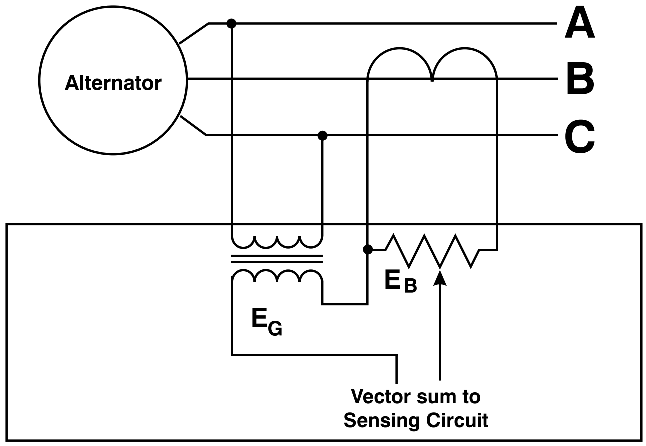


Figure 8: AVR with Droop

By building this characteristic into the regulator of each generator operating in parallel, sharing of the load is controllable and uncomplicated.

To parallel two generators, voltages should be matched prior to closing the breaker to minimize the current surge at breaker closing.

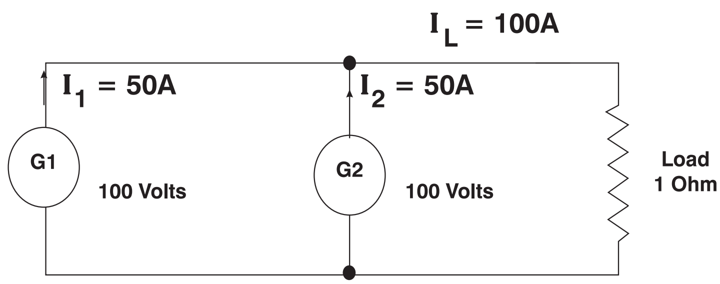


Figure 9: Paralleled Generators - Balanced Voltage

With voltages balanced and 100 Amperes load, each generator will supply its share of the load. If G2 voltage is increased, its output current will try to increase. This increase will cause a voltage droop, which counteracts the voltage increase. G1 will see its output current decrease, resulting in a droop circuit action to increase voltage. The result is a load balance control action that works to hold loading balanced when two or more generators are operating in parallel.

WHY CONTROL TWO VARIABLES?
KW, KVAR, KVA

In the dc analogy with batteries in parallel, only the voltage had to be controlled to allow for load sharing. In the mechanical ac analogy, only the torque had to be controlled. To parallel ac generators, both variables must be controlled properly. Torque applied to the generator must be controlled in order to divide real power (kilowatts); excitation to the generator must be controlled to divide the reactive power.

Real power is work done by the electrical energy of the generator. This power is supplied by the prime mover in the form of torque. The generator converts mechanical torque to electrical energy. This energy is supplied to a load to be converted to the desired form of energy, such as heat, light, mechanical energy (motor), etc.

Reactive power is that power required by loads with inductance or capacitance to store energy on each half cycle. In the example of Figure 10, the load is purely resistive, such as a heating element. Because no reactive power is required at any point on the sine wave, current is directly proportional to the voltage at that point. The real power can be calculated using Ohm's Law.

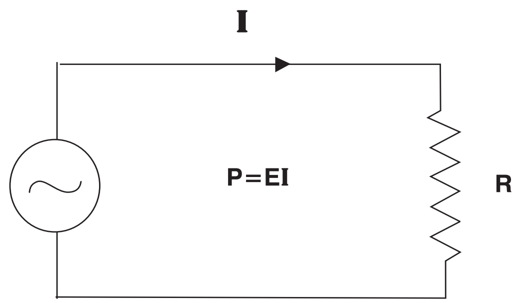


Figure 10: Resistive Load

If an inductance (Figure 11) is connected to the generator output, the relationship between voltage and current is different. The inductor will not allow current to flow without first building up lines of flux in its magnetic circuit. Thus, the current through the inductor is proportional to voltage, but the current lags the voltage by 90 electrical degrees (Figure 12).

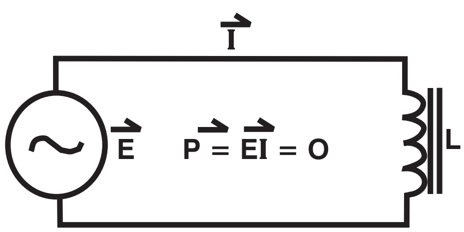


Figure 11: Inductive Load

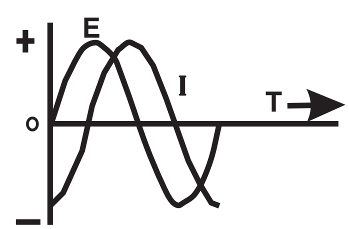


Figure 12: Current Lags Volts

The capacitor, on the other hand, will not allow voltage across its terminals until some charge has been deposited on its plates (Figure 13). For this reason, the current must flow before a voltage can exist. Thus the capacitor current leads the voltage by 90 electrical degrees (Figure 14).

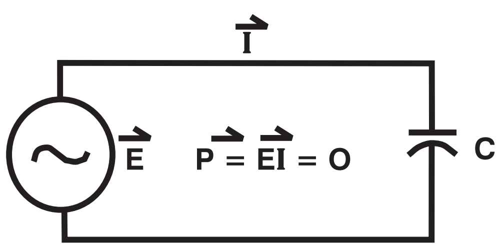


Figure 13: Capacitive Load

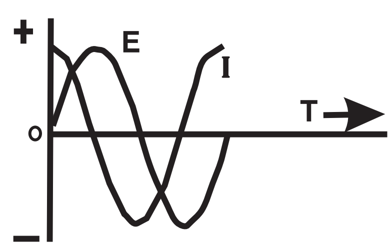


Figure 14: Current Leads Volts

For a load containing all three elements in parallel (Figure 15), it is convenient to calculate the real or reactive power in each element separately. The Law of Superposition (Figure 16) allows the addition of the three separate calculations vectorially to determine the total load.

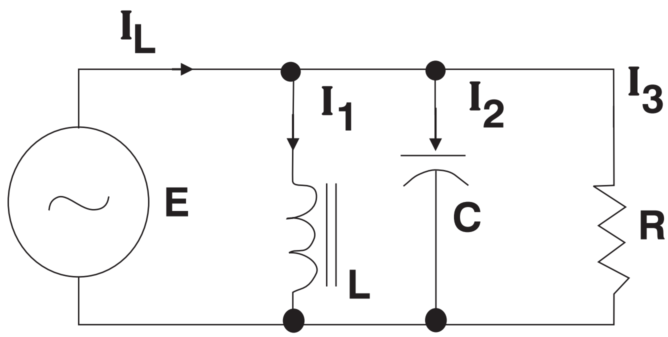


Figure 15: Combined RLC Load

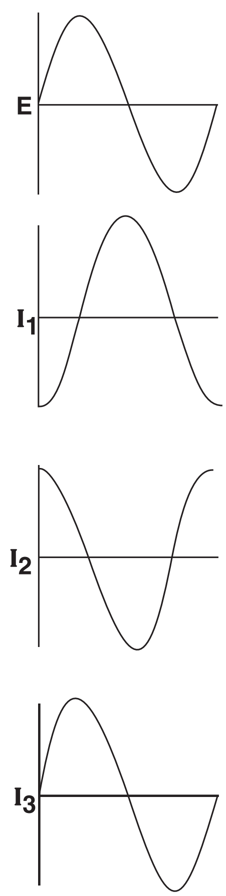


Figure 16: Law of Superposition

A look at I_1 and I_2 indicates that these currents are always opposite in polarity. If the currents are equal, the net result is *zero*! For this reason, inductive loads are said to accept reactive power, while capacitors are said to supply reactive power. Power Factor correction capacitors use this principle to compensate for inductive loading. The reactive power flow is illustrated in Figure 17.

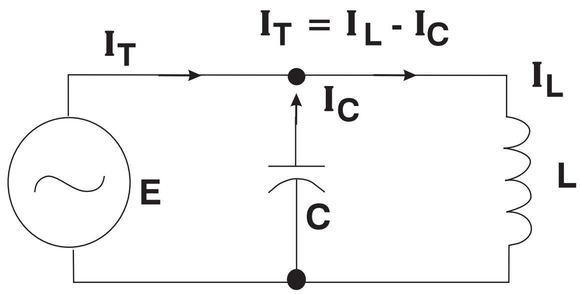


Figure 17: LC Loads

Thus, the reactive power, expressed in Vars, can be computed by:

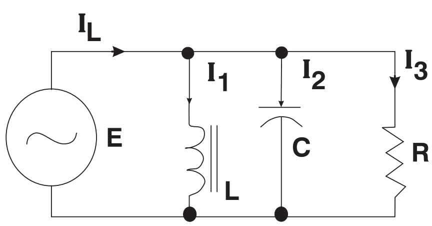
$$Q = \frac{E^2}{X_L - X_C} \qquad Q = \text{VARS } X_L - X_C$$

And the real power, expressed in watts, can be computed by:

$$P = \frac{E^2}{R}$$

P= Real Power, Watts

A third parameter can be computed by using the voltage of the generator and the current I_L in Figure 18. This parameter is known as "apparent power".



$S = EI_L$ (NO VECTORS)

S = APPARENT POWER, VOLT-AMPERES

Figure 18: Combined RLC Load

These three parameters, real, reactive, and apparent power, are related. Knowing any two, the third can be calculated using the Pythagorean Theorem:

$$S = \sqrt{P^2 + Q^2}$$

Or they may be calculated using vector arithmetic (Figure 19):

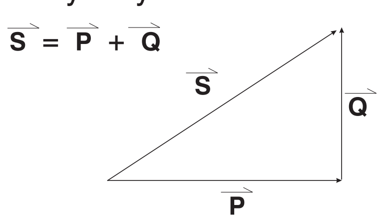


Figure 19A: Power Triangle

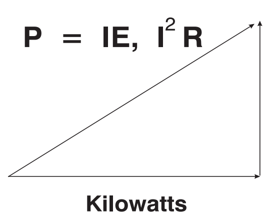


Figure 19B: Real Power - kilowatts

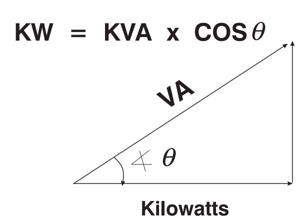


Figure 19C: Apparent Power - KVA

Metering is commonly provided to measure volts, amps and frequency for generators operating alone. For parallel application, monitoring current gives an indication of loading, but there is no indication of the type of current flow, making load sharing adjustment impossible. A meter to monitor real power in addition to current will enable power to be balanced by the governor adjustment, followed by balancing of current using voltage regulator adjustment. A better scheme adds an additional meter for reactive power, the Var meter. With a kW and Kvar meter on each generator, optimal adjustment of the governor and the voltage regulator are easily accomplished, and load sharing is easily monitored. Another metering option is the power factor meter, often used instead of the Kvar meter. Power factor is the ratio of real power to apparent power:

$$PF = \frac{P}{S}$$

P = REAL POWER, WATTS

S = APPARENT POWER, VOLT-AMPERES

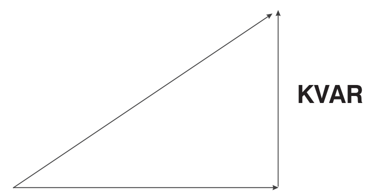


Figure 19D: Reactive Power - KVAR

Power factor, because it is affected by both real power and reactive power levels, is more difficult to interpret for monitoring load sharing performance. Providing good instrumentation is very helpful for operating systems of paralleled generators.

THE VOLTAGE REGULATOR AND PARALLEL GENERATOR OPERATION

The function of the voltage regulator is to provide precise regulated generator voltage at no load and with changing loads. When generators are connected together in parallel operation, a parallel compensation circuit is required to assist the voltage regulators in controlling the generator reactive loads.

Reactive loads between generators can become unbalanced when the voltage regulator varies the excitation to the generator exciter field due to load changes, prime mover speed variation, thermal drift, etc. This change in excitation may cause large “circulating currents” to flow between generators (Figure 20).

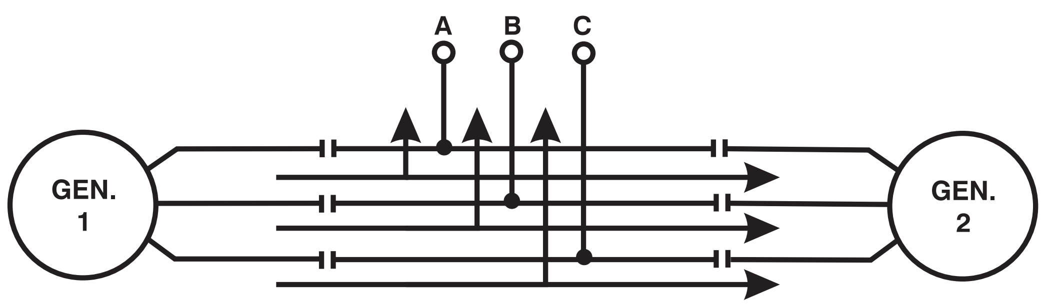


Figure 20: Circulating Currents

This causes the generator with the higher field excitation to try and power the generator with the lower field excitation in an effort to force the generator to have the same output voltage as the generator with the higher excitation.

The parallel compensation circuit will cause the voltage regulator to increase the field excitation on the generator with the lower field excitation and decrease the field excitation on the generator with the higher field excitation. By controlling the reactive load, the parallel compensation circuit can eliminate the undesired circulating currents.

Figure 21: Equal Pressure - A Unequal Pressure - B

An analogy of how one generator tries to power another generator with circulating currents can be compared to two water pipes of equal diameter feeding into one pipe. When the two water pipes have the same water pressure, both water pipes will be supplying the same amount of water to the common water pipe (Figure 21A). If one water pipe suddenly lost a small amount of pressure, the second water pipe would begin to supply more water to the common pipe to help maintain the water flow (Figure 21B). Also, because the water pressure in the second water pipe is now greater than the first water pipe, water will begin to flow from the second water pipe to the first water pipe in effort to force the water pressure to be the same as the second pipe.

REACTIVE DROOP COMPENSATION AND REACTIVE DROOP DIFFERENTIAL COMPENSATION

There are two forms of parallel compensation circuit. The most often used type of paralleling compensation is the parallel droop compensation or using the IEEE designation, reactive droop compensation. The other type is crosscurrent compensation or, again using IEEE terminology, reactive differential compensation.

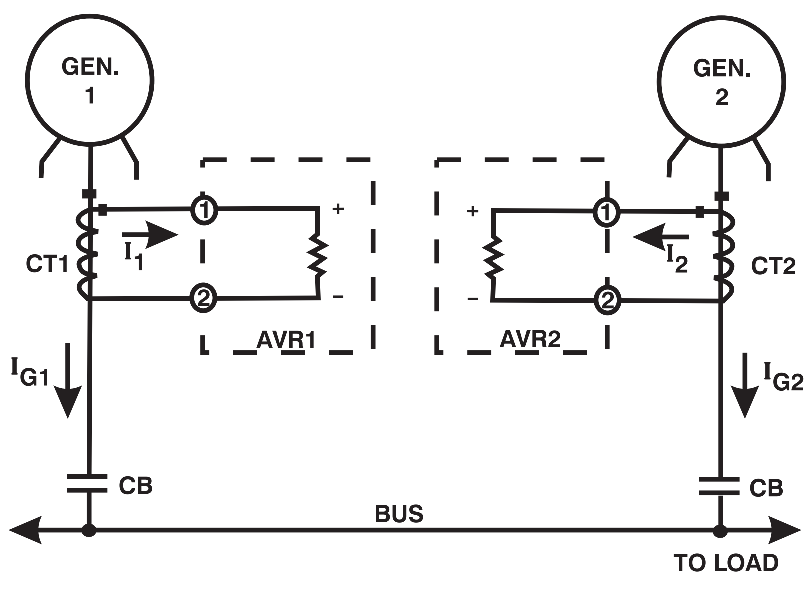


Figure 22: Reactive Droop Compensation

When reactive droop compensation is used to parallel two or more generators, each parallel droop circuit is independent of the other (Figure 22). A typical parallel droop circuit is made up of a current transformer and paralleling module. The paralleling module consists of a burden resistor and a switch connected across the primary of a transformer (Figure 23).

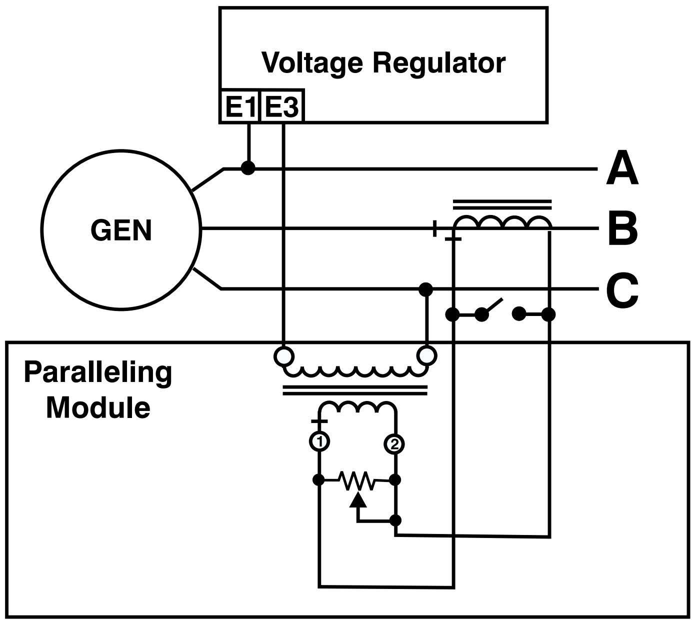


Figure 23: Paralleling Module

A switch located on the primary of the transformer in the paralleling module is used to short the secondary of the current transformer and the burden resistor to allow the generator to operate independently of the paralleling generating system.

The secondary of the current transformer is connected to the paralleling circuit. Connection to the paralleling circuit places a burden resistor across the output terminals of the current transformer (Figure 24). The secondary current of the current transformer induces a voltage across the burden resistor that is vectorially added to the line voltage to produce an error signal to the voltage regulator. Voltage across the burden resistor is proportional in magnitude and has the same phase as the line current through the primary of the current transformer.

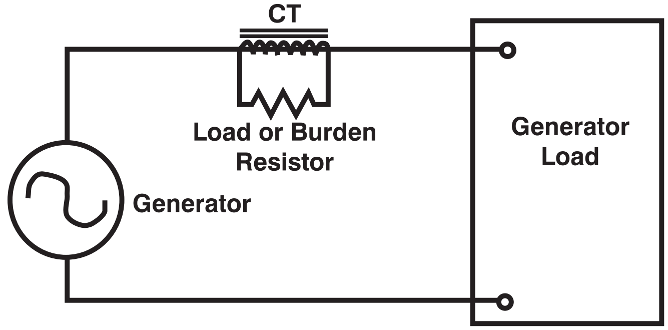


Figure 24: Burden Resistor

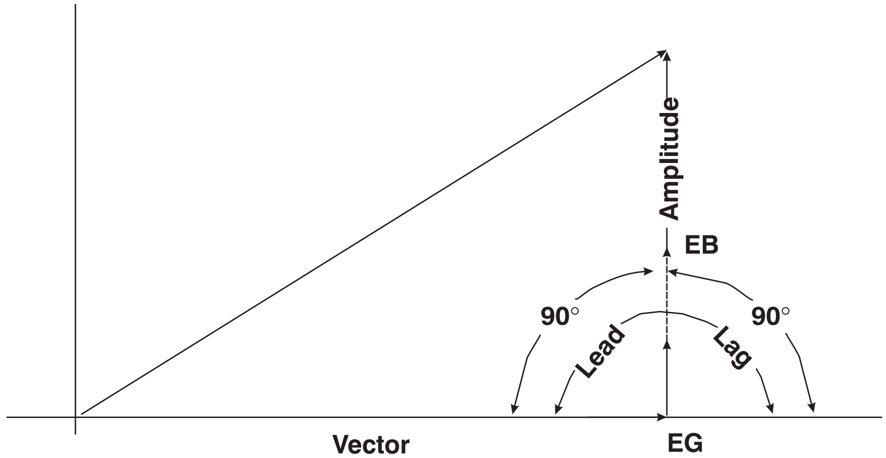


Figure 25: Current Transformer Error Signal Development

The error signal produced across the current transformer burden resistor must be applied so that when the load is a unity power factor load, no corrective signal will be produced and no excitation change will occur because of the load. By arranging the burden resistor voltage so that it will be 90 electrical degrees out of phase with the system voltage when the power factor of the load on the generator is unity, an appropriate error signal can be produced. Figure 25 shows the vector representation of system voltage and burden resistor voltage needed to produce the error signal.

The three phase voltages (line to neutral), regardless of their internal connections, produce output voltages that are displaced from each other by 120 electrical degrees. By taking advantage of the phase displacement, it is possible to sense the system voltage from line to line and produce a line voltage that is displaced from the phase voltage by 30 electrical degrees. The voltage signal from the current transformer burden resistor at unity power factor (resistive loads) will be displaced by 90 electrical degrees from the system or line voltage (Figure 26A).

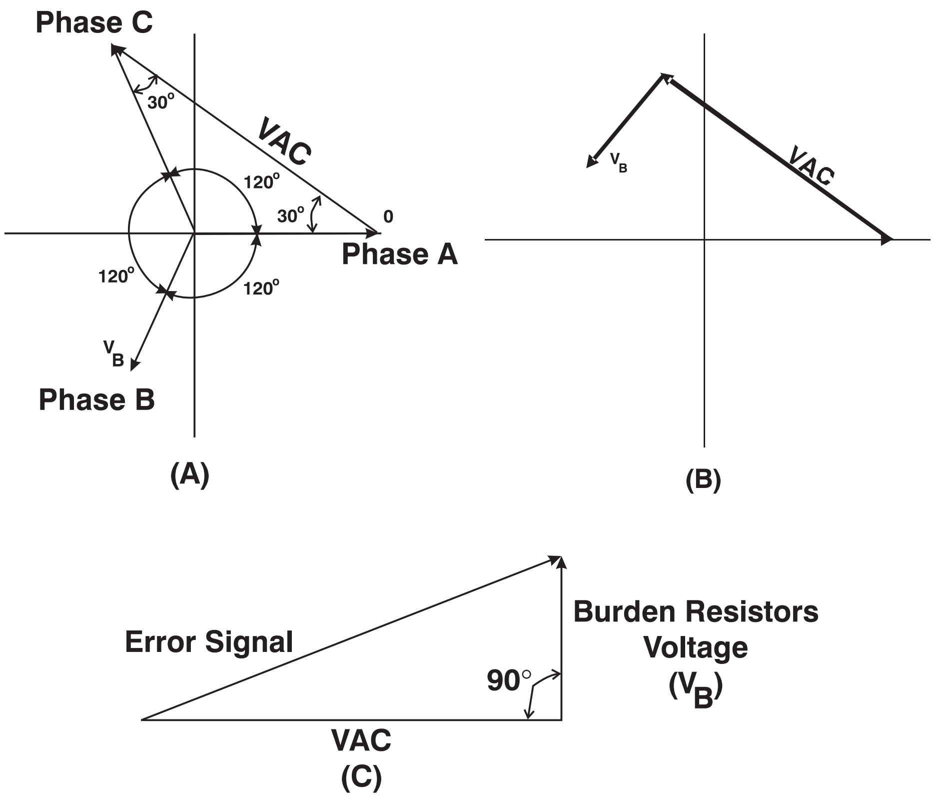


Figure 26: Phase Displacement

Under unity power factor, the vector diagram (Figure 26B) representation of the burden resistor voltage (V_B) and the sensing voltage (Vac) can be seen to be 90 electrical degrees apart. When a reactive load is applied to the generator, the burden resistor voltage arrow will swing either clockwise or counterclockwise depending upon the type of load, capacitive or inductive (Figure 26C).

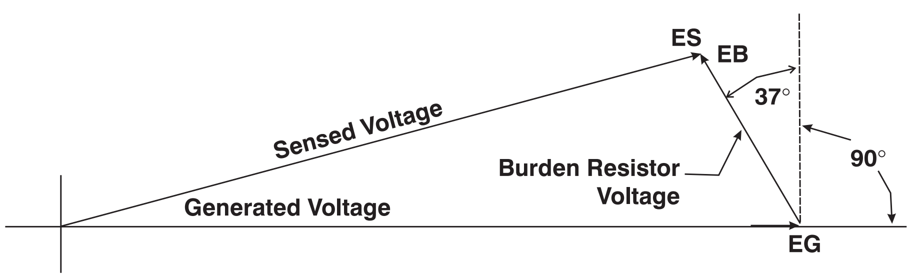


Figure 27: Vector Diagram of Capacitive Load

If the generator load has a leading power factor (capacitive load), the vector diagram of the burden resistor voltage will rotate counterclockwise from its unity power factor position (Figure 27). The phase angle between the line voltage and burden resistor voltage will become more out of phase, which will decrease the regulator sensing voltage. The regulator will receive a smaller sensing signal and thus increase generator excitation.

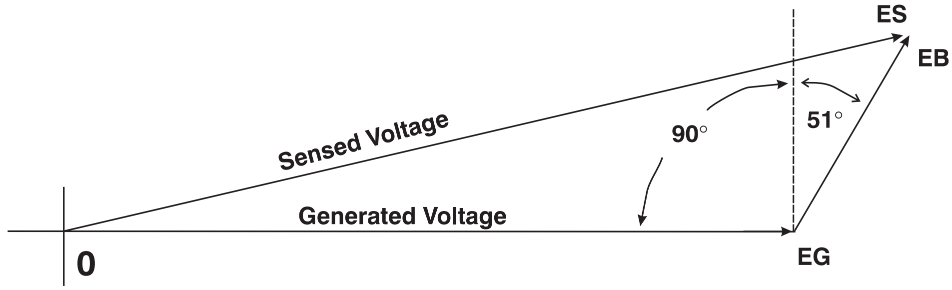


Figure 28: Vector Diagram of Inductive Load

When the load is a lagging power factor or inductive load, the vector diagram of the burden resistor voltage will be rotated clockwise from its unity power factor position (Figure 28). The phase angle between the line voltage and burden resistor voltage will become more in phase and the voltage sensing signal to the regulator will be increased. The regulator will receive the larger signal and respond by decreasing generator excitation.

The parallel module will supply an error signal to the voltage regulator that will control the excitation level of the generator. When the generators are paralleled, the regulator responds to this small increase in sensing voltage by reducing excitation to the generator field, which will produce a droop in the generator output voltage.

The amount a generator system will droop can be adjusted by the burden resistance and the current transformer ratio. A typical burden resistor has a resistance of one ohm and has an adjustable slide tap contact so that the voltage developed across the resistor can be varied. The amount of error signal sent to the voltage regulator is proportional to the magnitude of the voltage across the resistor and the vector angle of that voltage. The amount of voltage across the burden resistor is determined by the secondary or output current of the current transformer. Typical current transformers are designed for a 5 ampere secondary current with a 25VA maximum burden rating. Ohm's Law (Voltage = Current X Resistance) will show the maximum voltage across the one ohm burden resistor to be 5 volts. It can then be seen that the relative magnitude of the voltage developed across the burden resistor with full load on the generator is typically 5 percent of the system output voltage (120/208-240/416-480/600) to minimize circulating currents.

When generators are paralleled with reactive droop compensation, most generators are set to operate with maximum droop. The burden resistor is adjusted for maximum resistance or maximum voltage across the resistor. Allowing the generating system to operate at maximum droop allows for the best control of circulating currents. Setting the burden resistor for a system voltage droop of less than three percent may result in the regulator and paralleling circuit being unable to control circulating currents satisfactorily.

Voltage regulators with single phase sensing provide approximately 8% maximum droop while three phase sensing regulators provide approximately 6% droop. Single phase sensing provides greater droop because the average value of the error signal is proportionally greater compared to the average value of the single phase sensing voltage than to the average value of the three phase sensing voltage. When generators are paralleled on the same bus and have different type sensing, care must be taken to compensate for sensing differences using the adjustable burden resistor.

Since the burden resistance voltage is dependent on the line current of the generator through the current transformer, any changes in power factor due to the load will be reflected on the burden resistor voltage. Consequently, when a reactive lagging power factor load is increased, the bus voltage will droop by an increased amount. If a capacitive leading power factor load is increased, the bus voltage will increase. The magnitude of the change depends upon the magnitude of the load and power factor.

In order to prevent the voltage from increasing or decreasing with the power factor of the load, another circuit can be used where the current transformers of the individual regulators are interconnected. Crosscurrent compensation (reactive differential compensation) allows operation in parallel without voltage droop caused by the error signal.

Figure 29 shows two generators paralleled with reactive differential compensation. Interconnection of the current transformers can be seen. On generator number one, the current transformer (CT1) terminal with the polarity mark is connected to the current transformer (CT2) on generator number two at the terminal with no polarity mark. On generator number two, the current transformer (CT2) terminal with the polarity mark is connected to the current transformer (CT1) on generator number one at the terminal with no polarity mark.

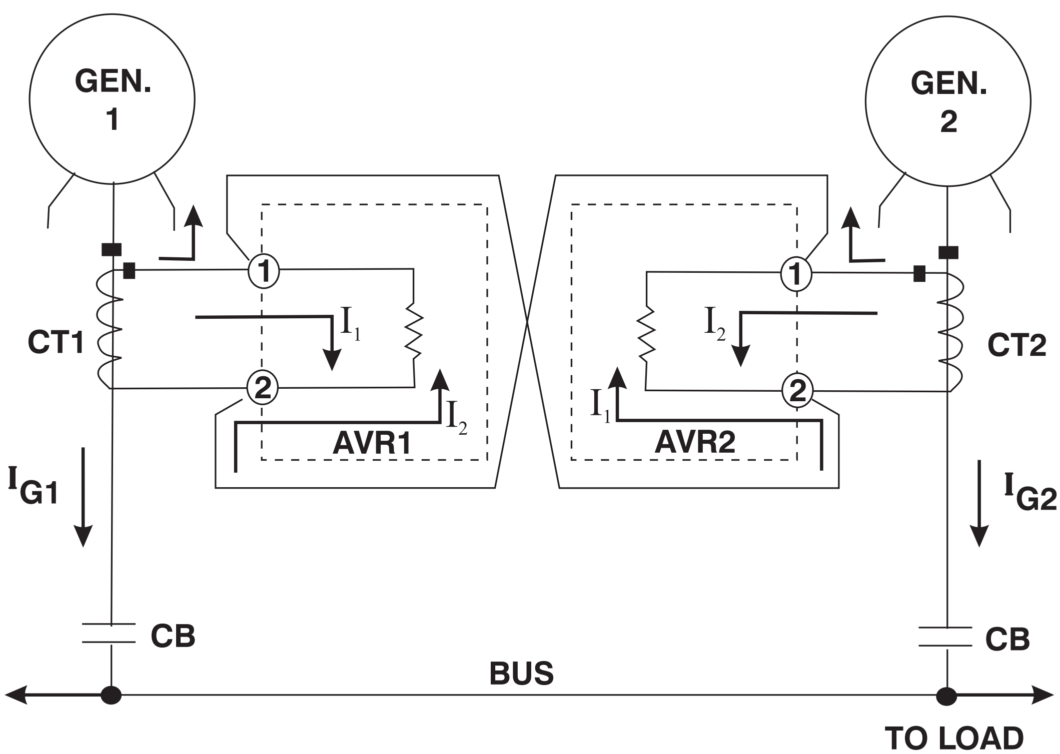


Figure 29: Two Generators Paralleled with Reactive Differential Compensation

Even though the voltage involved is ac, a better understanding of the operation of the closed crosscurrent loop can be obtained by using a dc voltage analysis. First of all, the polarity marks on the generator line and current transformer indicate the current direction. The line current always flows into the polarity mark on the generator line and the current flows out of the polarity mark on the current transformer (Figure 30).

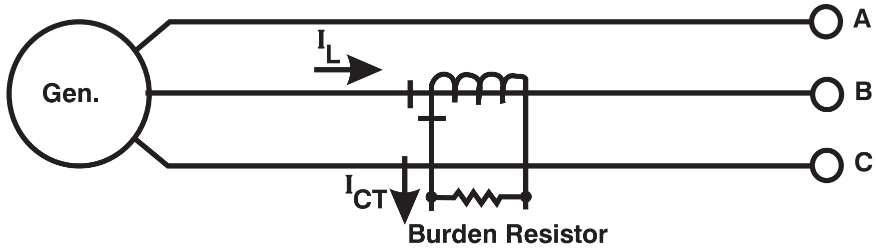


Figure 30: Burden Resistor

The current leaving the polarity marks of the current transformer are divided into two current paths (Figure 29). One circuit path flows through the burden resistor in the paralleling module. The second circuit path flows through the crosscurrent loop. The current that flows in the crosscurrent loop will enter the burden resistor in the adjoining parallel circuit and will oppose the current through the burden resistor set up by the paralleling circuit's own current transformer. The resulting current flow through the burden resistor in each paralleling circuit will be zero because the opposing currents will cancel each other out. Thus, there will be no voltage developed across the burden resistor and no droop associated with the line voltage.

If one generator begins to assume more reactive load than the other generator, the line current will increase and the current from the secondary of the current transformer will also increase. The result will cause a greater voltage across the burden resistor of the paralleling circuit, which will cause the voltage regulator to reduce the excitation in that particular generator, thus decreasing line current. An increase in current through the crosscurrent connect loop caused by the imbalance of the first generator will develop a voltage across the second generator's paralleling burden resistor that is opposite in polarity to the normal voltage developed by the second generator's own current transformer. Instead of causing a droop in line voltage, the opposite polarity will cause an increase in line voltage. The resulting increase in one generator and a decrease in the other generator will cause the parallel generating system to balance itself out.

For the reactive differential compensation to perform properly, all of the paralleling current transformers on all of the generators delivering power to the bus must be connected into the crosscurrent loop. The current transformer connected in the loop must have the same ratios so that each current transformer supplies the same amount of current to properly cancel the voltage across the burden resistor. In the case where different size generators are paralleled, current transformer ratios must be changed to give approximately the same secondary current as the other current transformer(s). Otherwise, cancellation of the currents in the crosscurrent loop will not occur, and the imbalance of current will force the generators to have circulating currents between them.

In addition to having the same current transformer ratios, all generators must have the same burden resistor setting in the voltage regulator paralleling circuit. Having the same burden resistor setting ensures that when an imbalance exists in the generators, the current that flows in the crosscurrent loop will setup a proportional voltage across each burden resistor that will balance the generator system's reactive load.

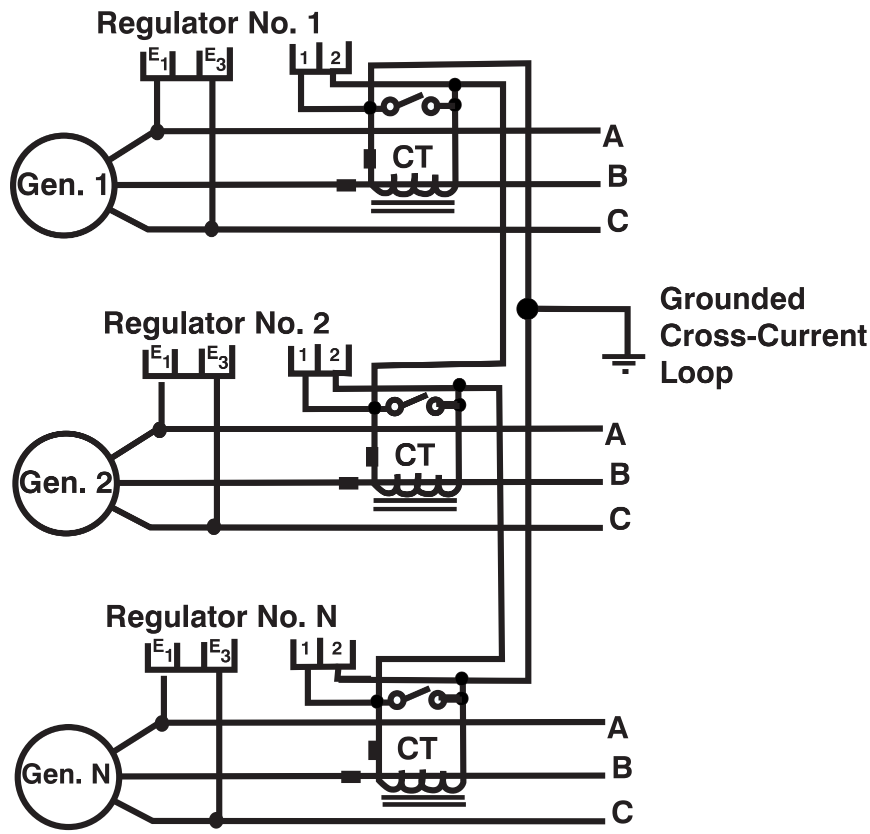


Figure 31: Reactive Differential Compensation Connection

In order to perform properly, the crosscurrent loop must have all the generators tied into the loop. It is virtually impossible to parallel with an infinite bus (utility). If the crosscurrent connected generating system was paralleled with the utility outside the crosscurrent loop, a switch contact installed at any point in the loop may be opened, and all generators will operate in droop mode.

For compliance with most safety codes, a ground connection is placed on the CT secondary. Only one ground can be installed on the loop, the current transformers will be shorted out (Figure 31).

Some means of isolation between the regulator sensing circuit and the current transformer circuit must be used with crosscurrent compensation circuits. Basler regulators and paralleling circuits include isolation transformers used to effectively isolate the crosscurrent loop from the input voltage circuit of the regulator.

THE CURRENT TRANSFORMER UNIT-PARALLEL SWITCH

A switch is placed on the secondary of the current transformer to short circuit the current transformer and the burden resistor, which will negate any signal to the generator. The switch in the “Unit” position allows the generator to operate independently of the parallel generating system without the effect of the droop circuit.

When a generator is operating independently in a parallel droop system and the short circuit switch is not in the “Unit” position, the generator will have an unwanted droop in the generator output voltage. The same effect will happen in a crosscurrent system only the droop will be smaller because other burden resistors in series act as a voltage divider to decrease the amount of voltage proportionally.

When generators are operating in a crosscurrent loop and one generator is taken out of parallel with the other generators to operate independently, the unit parallel switch is important to maintaining the stability of the remaining generators paralleled. If the non-paralleled generator is disconnected from the line with the current transformer and the burden resistor not shorted, the parallel system voltage will fluctuate. The generator not paralleled will be rotating at a different speed and frequency compared to the paralleled generators. The current through the burden resistor of the non-paralleled generator will have a constantly varying phase angle compared to the current through the paralleled generator burden resistors. The constantly changing phase angle across the burden resistor current of the non-paralleled generator will cause the non-paralleled regulator to alternately raise and lower the excitation of the non-paralleled generator. This will produce a small periodic change in excitation, which will increase and decrease that generator’s output voltage. The rate at which the voltage will fluctuate is equal to the difference in frequency from the non-paralleled generator and the paralleled generators.

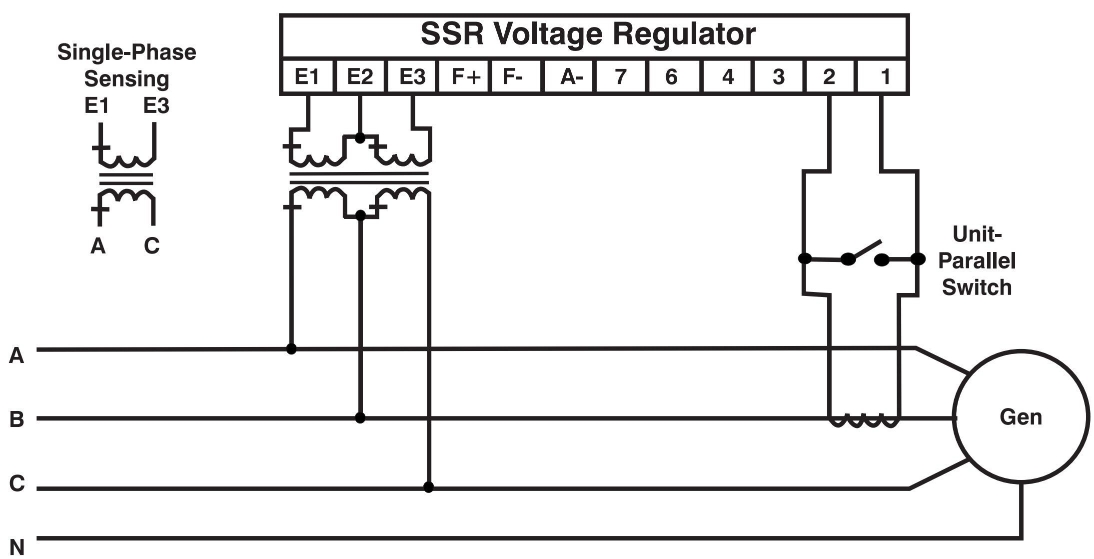


Figure 32: Unit - Parallel Switch

If a unit-parallel switch is to be added externally to a paralleling circuit, attention must be made to the distance the switch is to be placed from the current transformer secondary terminals (Figure 32). If a considerable distance is required for connection of the switch, resistance from the wire to and from the switch might be great enough to allow some of the current to pass through the burden resistor. If a small current is allowed to flow through the burden resistor, an equally small voltage will be produced across the burden resistor and produce a small droop in the system voltage, if the system is paralleled with reactive droop compensation. If so, reactive differential compensation is used to produce an effect similar to that just described for the crosscurrent loop in the preceding paragraph. Connections to the shorting switch should be made as short as possible.

Note: When operating with the reactive differential compensation circuit, it is desirable to have the unit parallel switch be an auxiliary contact on the main generator breaker. The auxiliary contact should be closed and the CT secondary shorted when the main generator breaker is open. The instant the main generator breaker closes connecting the generator in parallel, the auxiliary contact should open removing the short from the CT secondary allowing it to give the reactive load signal. This prevents any voltage droop from being introduced and eliminates the fluctuating voltage of the oncoming generator described earlier.

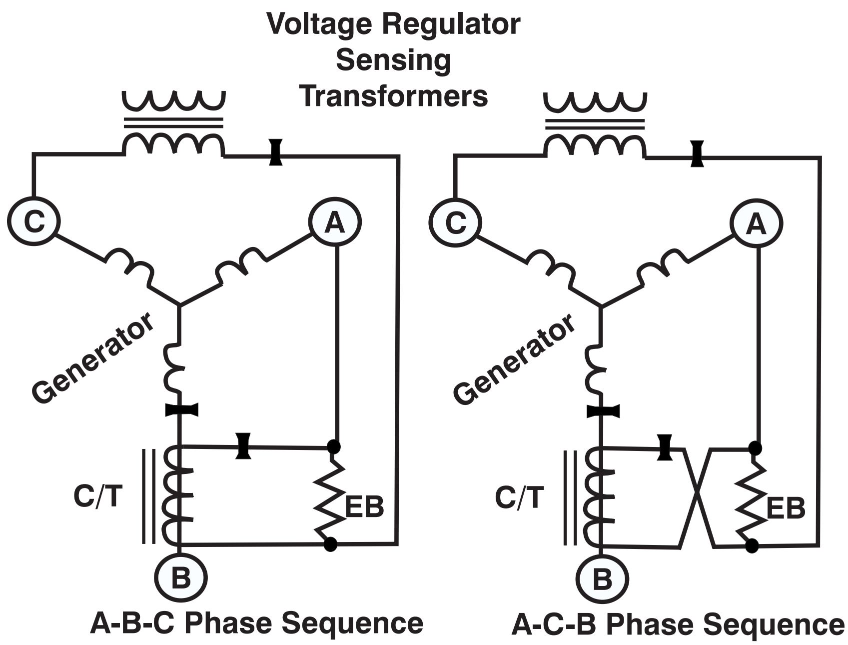


Figure 33: Generator Phase Sequence/Current Transformer Polarity Relationship

CURRENT TRANSFORMER PLACEMENT ON UNMARKED PHASES

As mentioned before, the current transformer can be connected to any phase of the generator as long as the system voltage is taken from the appropriate line voltage to maintain a 90 electrical degree phase difference with the burden resistor voltage. If it cannot be determined which generator lines are phase A, B, and C, the paralleling current transformer should be placed on the generator phase that does not supply sensing voltage to the regulator. If the regulator is set up with the generator for three phase sensing, the current transformer must be placed on the phase where the voltage regulator senses the B phase (Figure 33).

The polarity connection of the current transformer will be the determining factor to whether the generators are paralleled correctly if the phase rotation is undeterminable. If the current transformer is connected incorrectly, the generator will not droop but will rise in voltage under lagging inductive load.

If crosscurrent compensation is used to parallel the generators, it is recommended that the crosscurrent connecting loop be left open at one point until proper parallel option is achieved with the parallel droop compensation.

CURRENT TRANSFORMER SELECTION

Generators of different size KVA and line voltage have different line currents. When generators of different KVA are paralleled, current transformers used to parallel the generators must have correct current transformer ratios to provide nominal secondary current that is equal to other current transformers. A typical current transformer has a nominal 5 ampere secondary current with a maximum burden of 25VA. Obviously, to have a secondary current of 5 amperes, the primary current must be equal to the current rating of the primary. Matching current transformer ratios with line current to provide a nominal secondary current output from the current transformer is a detail that must not be overlooked. Table 1 shows the design specifications of typical current transformers.

When selecting a current transformer to step-down generator line current, if the line current falls between the current transformer primary ratings of two current transformers, the current transformer with the higher primary current rating should be selected. The reason for selection of the higher primary rating is to keep the current transformer within its maximum limits.

The problem caused by using a current transformer with a lower primary rating is that the higher line current will force a higher secondary current than the nominal 5 amperes. A secondary current that exceeds the nominal 5 ampere value can cause the burden of the paralleling circuit to be greater than the maximum designed burden rating of the current transformer. Excessive current can cause transformers to reach saturation, which will change inductance values of the transformers. The resulting change in inductance can alter the phase angle of the signal that is sent to the voltage regulator for paralleling, causing an improper response from the regulator.

On the other hand, it is also possible to select a current transformer with a primary rating that is too high. In such a case, the secondary current supplied to the paralleling circuit will be insufficient and paralleling operation can run uncontrolled or weak. Sometimes selecting a higher current transformer ratio and doubling the primary turns of the generator line can achieve a closer secondary current to the nominal 5 amperes.

For best selection of a current transformer, finding a current transformer with a current transformer ratio that will provide the closest possible current to the nominal 5 amperes is suggested. Satisfactory parallel operation can usually be achieved if a minimum of three amperes at full load rated power factor is provided.

Current Transformer Requirements - Droop

- Instrument accuracy
    - accurate magnitude
    - accurate phase
    - may be shared
- Ratio selected for minimum 3 amps (0.6 Amps)
- Ratio selected for maximum 5 amps (1.0 Amps)

CT Requirements - Cross Current Compensation

- Ratios equal for equal genset ratings
- Ratios proportional if unequal ratings
- Burden resistors same for all units
- No groundings in each secondary

CT Burden Requirements

- Basler's AVRs have burdens between 0.2 and 1 ohm, 5 amp or 1 amp nominal current.
- CT must have sufficient capacity to drive all loads, lead wire resistance.
- Breaker aux contact and wire must be low in resistance to short CT effectively.

Model Number	Current Ratio (Amperes)	ANSI Relay Class	ANSI Metering Class (60HZ)					Winding Resistance Ohms (25°C)	Net Weight (lbs)	Shipping Weight (lbs.)
			BO.1	BO.2	BO.3	BO.4	BO.5			
CT2	200:5	C10	0.6	0.6	1.2	2.4	-	0.075	9.0	11.0
	250:5	C10	0.3	0.6	1.2	1.2	2.4	0.093		
CT3	300:5	C10	0.3	0.3	0.6	1.2	2.4	0.112	9.0	11.0
	400:5	C20	0.3	0.3	0.3	0.6	1.2	0.149		
CT5	500:5	C20	0.3	0.3	0.3	0.6	1.2	0.186	9.0	11.0
	600:5	C20	0.3	0.3	0.3	0.3	0.6	0.224		
	750:5	C20	0.3	0.3	0.3	0.3	0.3	0.280		
CT10	1000:5	-	0.3	0.3	0.3	1.2	-	0.184	2.8	4.8
CT12	1200:5	-	0.3	0.3	0.3	0.6	1.2	0.245	2.9	4.9
CT15	1500:5	-	0.3	0.3	0.3	0.3	0.6	0.275	3.1	5.1
CT20	2000:5	-	0.3	0.3	0.3	0.3	0.3	0.34	3.3	5.3
CT30	3000:5	-	0.3	0.3	0.3	0.3	0.3	0.52	3.7	5.7
CT40	4000:5	-	0.3	0.3	0.3	0.3	0.3	0.70	3.9	5.9
CT50	5000:5	-	0.3	0.3	0.3	0.3	0.3	1.25	5.5	7.5

Table 1: Electrical Ratings

PARALLELING DIFFERENT SIZE GENERATORS

When generators of different KVA are paralleled, each generator will have a different line current. To parallel the different size generators, current transformers of different ratios will have to be used to step-down the different line currents to a standard nominal secondary current.

For droop operation, the droop adjustment is used so that each generator droops a like amount at its rated load. Then, the generators can be paralleled and each generator can be adjusted to carry its proportional share of the reactive load.
For generators paralleled with reactive differential compensation, equal currents are needed to cancel opposite currents so that no droop in the generating system is present. The unequal currents presented by the current transformers will force the cross-current loop to operate at an imbalance and maintain circulating currents. To decrease the imbalance of current through the cross-current loop, have all burden resistors set at maximum resistance. Then the burden resistor across the current transformer with the smallest secondary current should be adjusted for a smaller resistance so more current can flow

through the resistor. The burden resistor should only be adjusted for a small amount. Decreasing the burden resistance causes the response of the generator to be less sensitive to imbalances in the loop due to reactive loading. The burden resistor should only be adjusted a small amount so as to maintain proper control of circulating currents and also to decrease the current imbalance of the loop due to the current transformers.

It must be pointed out that if current transformer secondary current among generators varies only by a few tenths of an ampere, conditions will be such that the imbalance injected into the cross-current loop or parallel droop circuits will be neglectable.

PARALLELING GENERATORS

To illustrate the considerations and paralleling equipment necessary to parallel generator sets, the two following examples of parallel three generator systems are presented.

Two generating systems composed of three generators connected for parallel operation are illustrated in Figures 34 and 35. In Figure 35, the three generators are connected for parallel droop compensation; and in Figure 34, the three generators are connected for cross-current compensation. Both parallel generator systems have two 625 KVA generators with a kilowatt rating of 500 kW and one 125 KVA generator with a kilowatt rating of 100 kW.

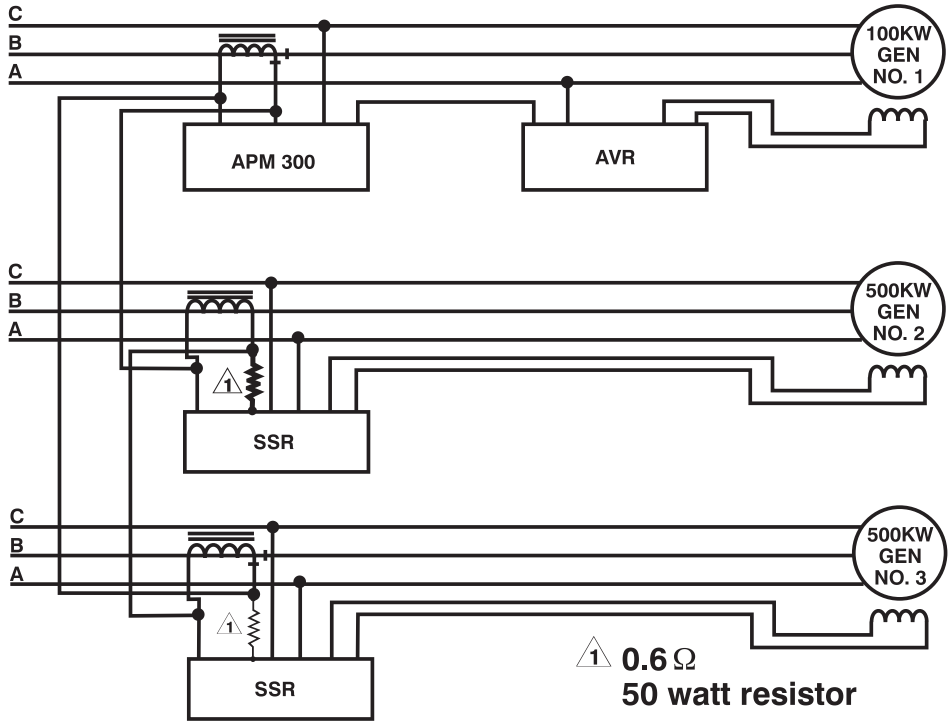


Figure 34: Cross-Current Compensation Connections

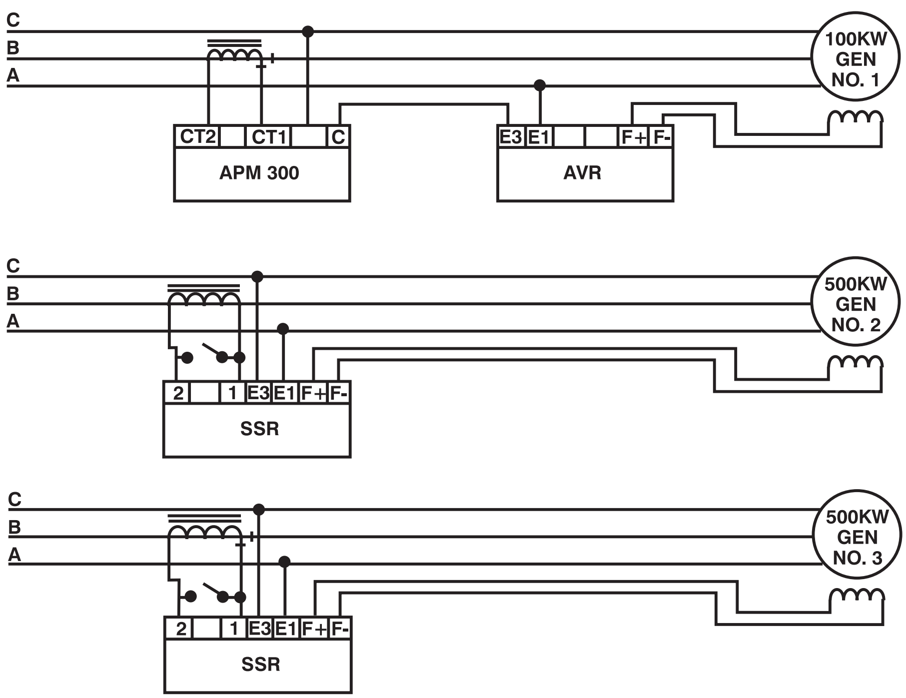


Figure 35: Parallel Droop Compensation Connections

Each generator has a line-to-line voltage of 480 volts so the generators can be connected to a common bus. From the given information about the generators, the current for each generator is calculated from the apparent power (KVA) of the generator.

$$KVA = 3\, I_L V_L$$

The current for the 500 KVA generators is 752 amperes, and the current for the 125 KVA generator is 150 amperes.

The voltage regulators chosen for the generators operating with parallel droop compensation were selected to illustrate that voltage regulators do not necessarily have to be the same to operate with parallel droop. Both the 625 KVA generators are regulated with Basler SSR regulators, and the 125 KVA generator is regulated with a generic voltage regulator.

Basler voltage regulators and paralleling modules feature a built-in isolation transformer for cross-current compensation. The isolation transformer is necessary to prevent the sensing circuit of the regulators from being paralleled by the cross-current connections between generators.

To determine how to add paralleling provision to a Basler regulator, Figure 35 can be used to make the selection. The SSR regulators that are used on the 625 KVA generators are equipped with paralleling provision as an option.

The generic regulator has no paralleling provisions built-in so a Basler APM 300 paralleling module will be selected.

The SSR voltage regulators equipped with paralleling provisions do not have a built-in unit/parallel switch to short out the current transformer and take the generator off-line or operate independent of the other generators. An external unit/parallel switch is added to the SSR voltage regulators.

To further illustrate paralleling different size generators in the cross-current mode, Figure 33 shows two Basler SSRs with a regulator of a different manufacturer or a Basler regulator with a different burden resistor value. To allow these generators to be connected in cross current, the burden resistors must match. This figure shows adding external resistors to the SSRs paralleling circuit to match burdens with the APM 300. We calculated this value using the following method.

METHOD FOR DETERMINING DROPPING RESISTOR VALUE WHEN CONNECTING DISSIMILAR REGULATORS IN CROSS-CURRENT COMPENSATION CONFIGURATION

1. Start with the VA rating and current signal of each regulator and find its equivalent resistance.

   Example: SSR Regulators: 10 VA, 5 Amps

   $V = \frac{VA}{A} = \frac{10}{5} = 2$ Volts; $R = \frac{V}{A} = \frac{2}{5} = 0.4$ ohms

   Other regulator: 25 VA, 5 Amps

   $V = \frac{VA}{A} = \frac{25}{5} = 5$ Volts; $R = \frac{V}{A} = \frac{5}{5} = 1.0$ ohms

2. Take the regulator with the lowest VA rating (Voltage "V") and determine the value of series resistance necessary to drop the applied voltage from the larger VA rating to that required by the present regulator. See figure below.

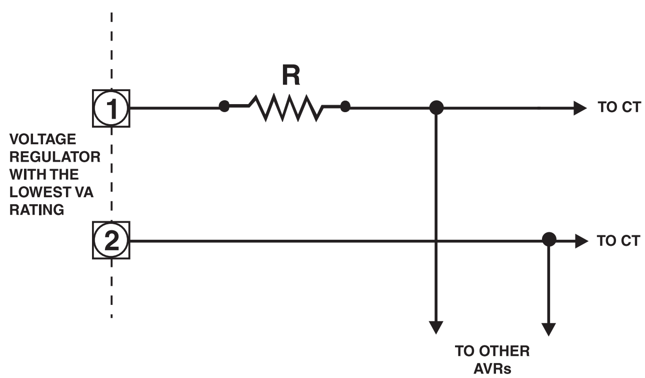


Figure 36: Voltage Regulator with External Matching Resistor

From previous example: 2V, 0.4 Ohms; 5V, 1.0 Ohms

The required voltage is 2 volts but the supplied voltage is 5 volts; therefore, the series resistor should drop 3 volts:

$$V_{Required} = V_{Supplied} \frac{RRegulator}{R_{Regulator} + R_{Series}}$$

$$2 = 5 \frac{0.4}{0.4 + R_{Series}}$$

$$2 (0.4 + R_{Series}) = 5 (0.4)$$

$$0.4 + R_{Series} = 1$$

$$R_{Series} = 0.6 \text{ Ohms}$$

The wattage of the series resistor can be calculated from:

$$W = I^2 R$$

$$W = 5^2\, 0.6 = 15 \text{ Watts}$$

Since we derate our resistors by 50%, the required wattage will be 30 watts. The next standard wattage value is 50 watts.

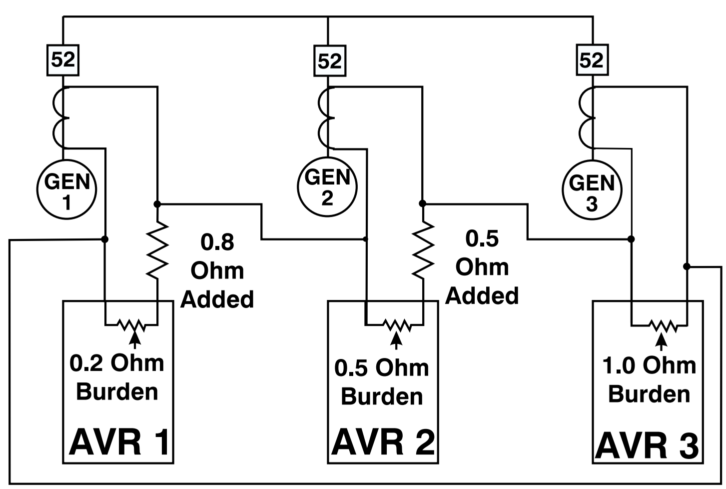


Figure 37: Parallel Generator Setup

TROUBLESHOOTING PARALLELING

Abnormal indications

- Immediate increase in current
- Difficult to adjust voltage adjust for null
- Changing loads cause unbalance

For immediate high current

- Check paralleling in droop only
- Verify that kW load is properly shared
- Check SENSING connections to AVR
- CT in correct phase??
- Reverse CT secondary polarity
- Try to parallel again
- If all above is OK, try to close cross current loop

Correct CT polarity??

- Place CT on correct phase
    - No sensing connection, or
    - E2 sensing connection
- If CT is on correct phase, polarity is:
    - Correct, and closing breaker works okay, or
    - Reversed, and closing breaker causes immediate high current
- Wrong phase, possibilities MULTIPLY!!!

Finding the problems

- Check for small voltage across droop input. CT may be shorted somewhere.
- Check droop adjust. Max or min??
- Check polarity marks on PTs with small battery and voltmeter
- Verify PT connections, CT in correct phase

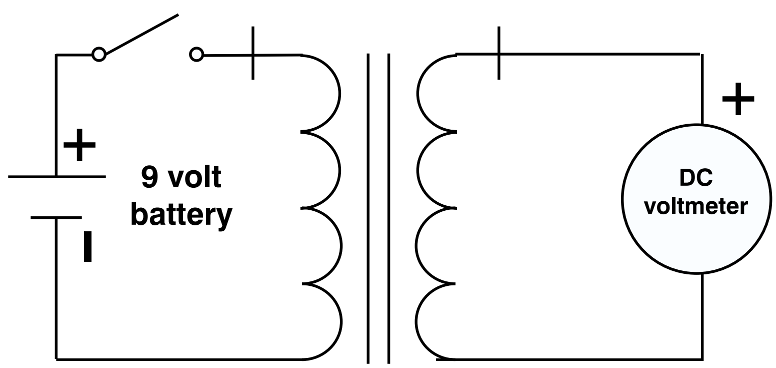


Figure 38: Potential Transformer Polarity Check

Another test

- OK to parallel without any droop on one machine, with careful attention.
- Check to see that two machines can share load if only one of the droop CTs is not shorted.
- If loading is possible, check for direction of droop by increasing drooping AVR voltage adjust.

Another test

- Connect oscilloscope to E1 and E3, channel 1
- Connect channel 2 to Droop input, 1 and 2
- With some resistive load current, observe 90° phase shift from voltage to current

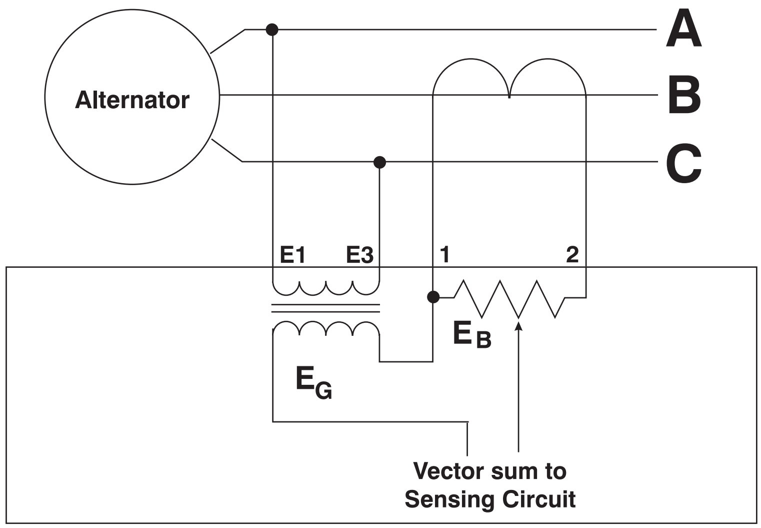


Figure 39: AVR with Droop

Checking and Troubleshooting a Reactive Compensation Circuit for the Automatic Voltage Regulator for Isolated AC BUS

Typical Problem!

Excessive circulating current between generators connected to an isolated bus. Shutdown generators; verify system is connected for "Reactive Droop" per figure. Check potential transformer and current transformer for proper connection and phasing.

Open breakers and start turbine/generator, turn on AVR and bring generator voltages to normal value. Measure field voltage on both generator 1 and 2 and record.

Match voltage, frequency, and phase angle. Then synchronize generators.

Measure field voltage after breakers close, note zero Vars and zero kW assuming the system has "no connected load". ⚠1

If generator vars and generator line current exhibit little change, field voltage will change little. System is okay.

If generator vars drastically increase accompanied by sudden increase in generator line current, problems exist in AVR reactive droop compensation circuit. ⚠2

If generator vars tend to drift between machines after a time period, check field voltage and note the same drift.

Problem caused by
1. Current transformer in wrong generation line with respect to voltage sensing. Recheck interconnections of PT, CT to AVR.
2. Current transformer is not providing 3-5A signal at full load rated power factor. Check CT ratio for 3-5 amps at full load rated KVA
3. Current transformer not in CT circuit of AVR. Signal may be shorted somewhere in the system. Check for 3-5 Amp signal at terminals 1 and 2 of AVR rated power factor rated load. Measure 3-5 volt drop across one ohm burden resistor in AVR paralleling circuit at full load on generator.
4. Droop adjustment of voltage regulator set for insufficient droop.

Open generator breakers short CT1 on Generator 1. Match voltage frequency and phase angle on Generator 1 with Generator 2. → If a differential compensation circuit is being used, disconnect.

If generator vars goes up on generator, open breakers, shut down generators, and reverse CT2.

Restart, resynchronize and close generator breaker. Field voltage should now essentially show the same as prior to closing generator breaker. If so, system is okay.

If generator vars stay constant, parallel circuit of Generator 2 is okay.

Open generator breakers, unshort CT1, and short CT2.

Match voltage, frequency and phase angle of generators 1 and 2. Close breakers.

If vars increase, open generator breakers, shut down generators, and reverse CT1 connection.

Restart generators, match voltage, frequency and phase angle. Resynchronize generators. Field voltage should now show the same as prior to closing generator breaker.

Open generator breakers, remove shorted connection at CT2. Match generator voltage, frequency and phase angle. Resynchronize machines.

Apply rated .8PF load to generator. The terminal voltage should droop approximately 5% for rated power factor load. →

If generator still shows high circulating currents, check for the following:
1. Interconnection error on PT and CT connection, reverify.
2. Improper phasing of generator potential transformers.
3. Verify the CT circuit exists for the AVR. It may be shorted somewhere in the system.
4. Review governor operation. If high circulation currents remain, it may be due to the governor malfunction.

Notes:

⚠1 In those systems where testing must be performed with load similar test results will be anticipated using this procedure. The main difference will be field voltage will increase to loaded field voltage value after generator break closes. the magnitude depends on generator.

⚠2 The increase of generator vars will be lagging power factor caused by maximum field voltage from AVR or leading power factor caused by zero field voltage.