Applying 100% Stator Ground Fault Protection by Low Frequency Injection for Generators

Steve Turner, Senior *Member, IEEE*

Abstract— **This paper covers practical considerations for proper application of this protection for a variety of different applications. The total capacitance to ground of the generator stator windings, bus work and delta-connected transformer windings of the unit transformer is a very important factor and must be known to ensure the protection settings are correctly determined. It will be shown that unless special steps are taken in the design of this protection, there are cases when it is hard to distinguish between normal operating conditions and an actual ground fault. The protection must also reject fundamental frequency (50 or 60 Hz) voltage and current signals that are present during ground faults on the stator windings. A real-life example for a back-to-back start at a pump storage facility, captured via relay oscillography, is included.**

Index Terms—**stator ground fault protection, 20 Hz signal generator, bandpass filter, total capacitance to ground, stator windings insulation resistance to ground, grounding transformer turns ratio, neutral resistor, 20 Hz neutral current, 20 Hz neutral voltage, oscillography**

I. INTRODUCTION

One hundred percent stator ground fault protection is provided by injecting a 20 Hz voltage signal into the secondary of the generator neutral grounding transformer through a band-pass filter. The band-pass filter passes only the 20 Hz signal and rejects out-of-band signals. The main advantage of this protection is 100% protection of the stator windings for ground faults—including when the machine is off-line (provided that the 20 Hz signal is present).

II. APPLICATION

Fig. 1 illustrates a typical application. A 20 Hz voltage signal is impressed across the grounding resistor (RN) by the 20 Hz signal generator. The band-pass filter only passes the 20 Hz signal and rejects out-of-band signals. The voltage across the grounding resistor is also connected across the voltage input (VN) of the 64S relay. The current input (IN) of the 64S relay measures the 20 Hz current flowing on the grounded side of the grounding transformer and is stepped down through a CT. It is important to note that the relay does not measure the 20 Hz current flowing through the grounding resistor. The 20 Hz current increases during ground faults on the stator winding and an overcurrent element that operates on this current provides the protection.

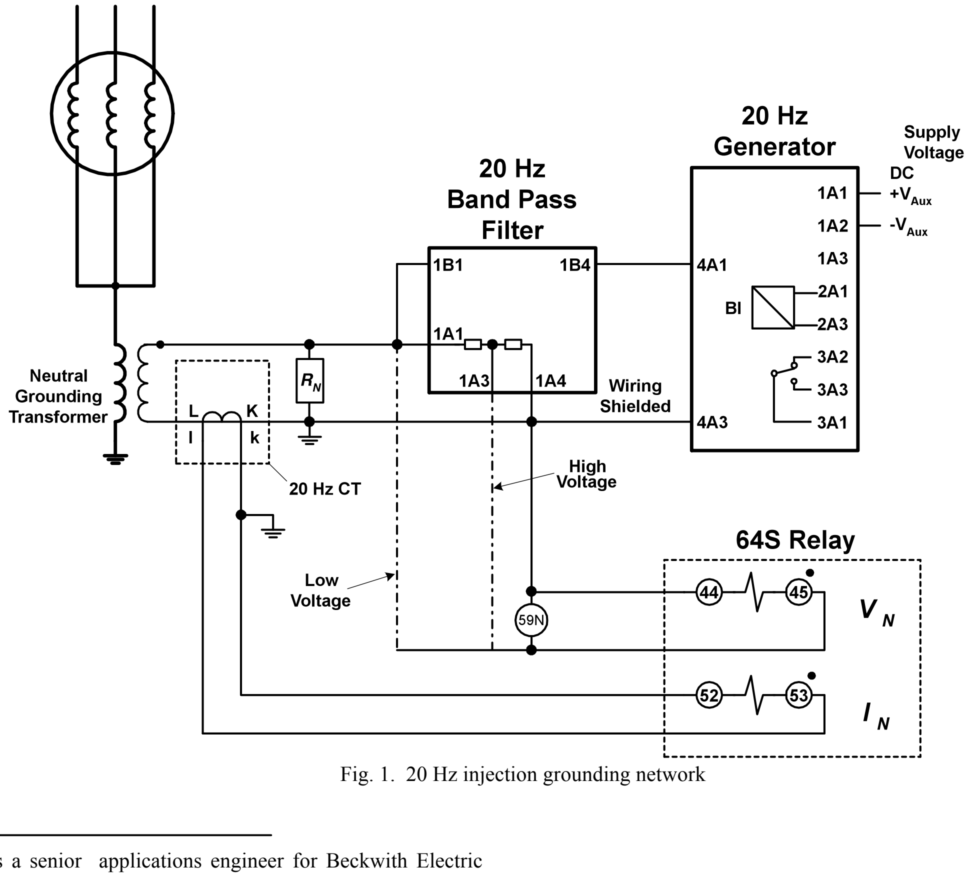

Fig. 1. 20 Hz injection grounding network

Steve Turner is a senior applications engineer for Beckwith Electric Co., 6190-118th Ave. N., Largo, FL 33773 U.S.A. (e-mail: sturner@beckwithelectric.com).

20 Hz Voltage and Current 64S Relay Measurements

The following shows how to calculate the 20 Hz voltage and current measured by the 64S relay.

Grounding Transformer Turns Ratio (N): Assume that the turns ratio of the grounding transformer is equal to:

$$N = \frac{8{,}000}{240} \tag{1}$$

Capacitive Reactance: The total capacitance to ground of the generator stator windings, bus work and delta connected transformer windings of the unit transformer is expressed as C_0. Generator step up transformers have delta connected windings facing the generator so capacitance on the high side is ignored. The corresponding capacitive reactance is calculated as follows:

$$X_{c0} = \frac{1}{2\pi f_0 C_0} \tag{2}$$

The capacitive reactance for 1 micro-Farad is equal to:

$$X_{c0} = \frac{1}{2 \bullet \pi \bullet (20\,Hz) \bullet (10^{-6}\,F)}$$

$$= 7{,}958\ \Omega \text{ primary}$$

Reflect the capacitive reactance to the secondary of the grounding transformer:

$$X_{c0} = \frac{7{,}958\,\Omega}{N^2} = \frac{7{,}958\,\Omega}{\left(8{,}000/240\right)^2}$$

$$= 7.162\ \Omega \text{ secondary}$$

Grounding Resistor (R_N): The ohmic value of the grounding resistor can be sized as follows so as to avoid high transient over-voltage due to ferroresonance:

$$R_N = \frac{X_{c0}}{3} \tag{3}$$

[1]

$$R_N = \frac{7.162\,\Omega_{sec}}{3} = 2.387\ \Omega \text{ secondary}$$

A value of 2.5 ohms secondary is used for this example.

20 Hz Signal Generator and Band-pass Filter Characteristics: Assume that the 20 Hz signal generator outputs 25 volts. The band-pass filter has a resistance equal to 8 ohms.

$$V = 25\ \angle 0° \text{ volts} \tag{4}$$

$$R_{BPF} = 8\ \Omega \text{ secondary} \tag{5}$$

Stator Insulation Resistance (R_S): R_S is the insulation resistance from the stator windings to ground. *A typical value for non-fault conditions is 50,000 ohms primary.*

$$R_S = \frac{50{,}000\,\Omega_{pri}}{N^2} = \frac{50{,}000\,\Omega_{pri}}{\left(8{,}000/240\right)^2}$$

$$= 45\ \Omega \text{ secondary}$$

Current Transformer: The current input (I_N) of the 64S relay measures the 20 Hz current flowing on the grounded side of the grounding transformer and is stepped down through a CT.

$$CTR = 80/1 \tag{6}$$

Grounding Network: Now there are all of the elements needed to mathematically represent the grounding network and determine the 20 Hz signals measured by the 64S relay.

Fig. 2A shows the insulation resistance and the stator windings referred to the primary of the grounding transformer.

Fig. 2B shows the insulation resistance and the stator windings referred to the secondary of the grounding transformer.

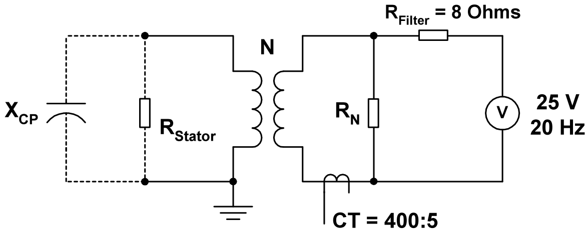

Fig. 2A. 20 Hz grounding network –referred to primary of grounding transformer

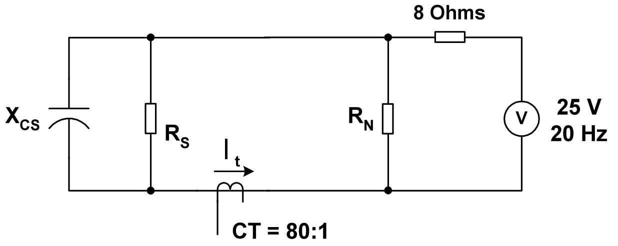

Fig. 2B. 20 Hz grounding network –referred to secondary of grounding transformer

20 Hz Current (I_N) Measured by 64S Relay: The current input (I_N) of the 64S relay measures the 20 Hz current flowing on the grounded side of the grounding transformer and is stepped down through a CT. As noted previously, the relay does not measure the 20 Hz current flowing through the grounding resistor.

Total 20 Hz Current Supplied by Signal Generator—The 20 Hz signal generator looks into the band-pass filter resistance (R_{BPF}) which is in series with the parallel combination of the following:

- Z_{c0}
- R_S
- R_N

Therefore, the total loop impedance of the 20 Hz grounding network can be expressed as follows:

$$Z_T = R_{BPF} + R_N//R_S//Z_{c0} \tag{7}$$

$$Z_T = 8 + (2.5)//(45)//(-7.162j) =$$
$$10.135 - 0.706j\ \Omega \text{ secondary}$$

The total 20 Hz current supplied by the signal generator is determined as follows:

$$|I_T| = \left|\frac{V}{CTR \bullet Z_T}\right| \tag{8}$$

$$|I_T| = \left|\frac{25\angle 0^\circ V}{\frac{80}{1} \bullet (10.135 - 0.706j\,\Omega)}\right| = 30.759 \text{ mA}$$

20 Hz Current Measured by 64S Relay (I_N) during Non-Faulted Conditions—The 20 Hz current measured by the 64S relay is the ratio of the total current that flows into the primary side of the grounding network ($Z_{c0}//R_S$):

$$|I_N| = \left|I_T \bullet \frac{R_N}{R_N + Z_{c0} // R_S}\right| \tag{9}$$

$$|I_N| = \left|30.579 \bullet \frac{2.5}{2.5 + (-7.162j)//(45)}\right|$$
$$= 9.779 \text{ mA } (\textit{Non-Faulted})$$

20 Hz Current Measured by 64S Relay (I_N) during Ground Fault on Stator Windings—A typical value to represent the insulation resistance of the stator windings breaking down during a ground fault is 5,000 ohms primary. If the calculations for Equations 7 through 9 are repeated for a fault resistance equal to 5,000 ohms primary (4.5 ohms secondary), then the 20 Hz current measured by the relay is as follows:

$|I_N| =$ 13.486 mA (*5,000 ohm primary ground fault*)

If the calculations for (7) through (9) are repeated for a fault resistance equal to 1,000 ohms primary (0.9 ohms secondary), then the 20 Hz current measured by the relay is as follows:

$|I_N| =$ 26.640 mA (*5,000 ohm primary ground fault*)

Table 1 summarizes the 20 Hz current measured by the relay for non-faulted and faulted conditions.

TABLE 1
20 Hz Current Measurements

R_S (primary)	$|I_N|$ (secondary)
50,000 Ω	09.779 mA
5,000 Ω	13.486 mA
1,000 Ω	26.640 mA

Set the pickup of the 64S relay overcurrent element above the current measured during normal operating conditions but below the current measured for a ground fault equal to 5,000 ohms primary.

III. PRACTICAL CONSIDERATIONS

There are three additional important aspects to consider when applying 100% stator ground fault protection by 20 Hz injection:

- slight change in fault current measured by relay
- rejection of fundamental frequency (50 or 60 Hz) voltage and current signals
- under-frequency inhibition

Slight Change in Fault Current

A very large system capacitance (C_0) and a small value for the grounding resistor (R_N) can result in very little margin between the fault and non-fault current measured by the relay. Consider the following grounding network parameters:

$$N = \frac{8{,}000}{240}$$

$C_0 = 10\ \mu F \rightarrow Z_{c0} = -0.716j\ \Omega$ secondary

$R_N = 0.25\ \Omega$ secondary

Determine the 20 Hz current measured by the 64S relay for non-faulted and ground fault conditions using the equations presented in the application section.

TABLE 2
20 Hz Current Measurements for High Capacitance

R_S (primary)	$|I_N|$ (secondary)
50,000 Ω	12.465 mA
5,000 Ω	12.096 mA
1,000 Ω	12.863 mA

The 64S relay overcurrent element pickup cannot be set such that it can reliably discriminate between non-faulted and ground fault conditions. *The solution is to calculate the real component of the 20 Hz current measured by the 64S relay*. To do so, first determine the 20 Hz voltage measured by the relay voltage input (V_N). The 20 Hz voltage is equal to the drop across the grounding resistor due to the ratio of the total current flowing through this branch of the grounding network.

20 Hz Current Flowing through the Grounding Bank

$$I_{Bank} = I_T - I_N \tag{10}$$

20 Hz Voltage Drop Across the Grounding Resistor

$$V_N = I_{Bank} \bullet R_N \tag{11}$$

Real Component of 20 Hz Current Measured by 64S Relay

Calculate the real component of the relay current based upon the angle between the relay voltage and current.

$$\varnothing = \angle V_N - \angle I_N \tag{12}$$

$$I_{Real} = |I_N| \bullet \text{COS}(\varnothing) \tag{13}$$

TABLE 3
20 Hz Current Measurements for High Capacitance Including Real Component

R_S (primary)	$|I_N|$ (secondary)	Re(I_N)
50,000 Ω	12.465 mA	0.198 mA
5,000 Ω	12.096 mA	1.900 mA
1,000 Ω	12.863 mA	8.001 mA

An overcurrent element that operates on the real component of 20 Hz current measured by the 64S relay can reliably distinguish between non-faulted and ground fault conditions when there is high-capacitive coupling to ground on the stator winding. *To decide if the real component of 20 Hz current is necessary, a good rule of thumb is if* C_0 *is greater than 1.5 micro-Farads and the grounding resistor is less than 0.3 ohms secondary*. The user can follow the commissioning instructions that appear at the end of this paper to determine the total capacitance to ground (C_0). If the values for R_N and C_0 do not clearly fall under the category defined by this rule of thumb then use the equations provided earlier in this paper to determine if the real component of neutral current is necessary.

64S should have an overcurrent element that operates on the total neutral current I_N and another overcurrent element that operates on the real component of I_N. The user should be able to enable either overcurrent element.

Rejection of Fundamental Frequency (50 or 60 Hz) Voltage and Current Signals: Fundamental component voltage and current present at the relay measuring inputs during stator ground faults can cause the 64S relay to not operate properly unless they are well rejected. Note that these signals are not eliminated by the band-pass filter since they are due to the voltage drop across the secondary of the grounding transformer.

Fig. 3 illustrates the fundamental voltage drop (50 or 60 Hz) across the grounding resistor as a function of the ground fault location along the stator windings. Table 4 shows the voltage drop as the fault location moves from the neutral side of the stator windings to the phase side. Assume the grounding transformer is rated 110 volts secondary, the grounding resistor is sized 0.32 ohms secondary and the CT ratio is 80:1. The corresponding fundamental component circulating current is shown as well. If the fundamental current is not well rejected, then high current can saturate the CT inside the 64S relay and the protection will measure a value of 20 Hz current less than the actual. Saturation causes the following problems:

- Delayed operation or, even worse, no operation at all
- *Less than 100% coverage of the stator windings* as the ground fault location moves towards the phase side

Saturation is most likely to occur when the grounding resistor is sized less than one ohm secondary.

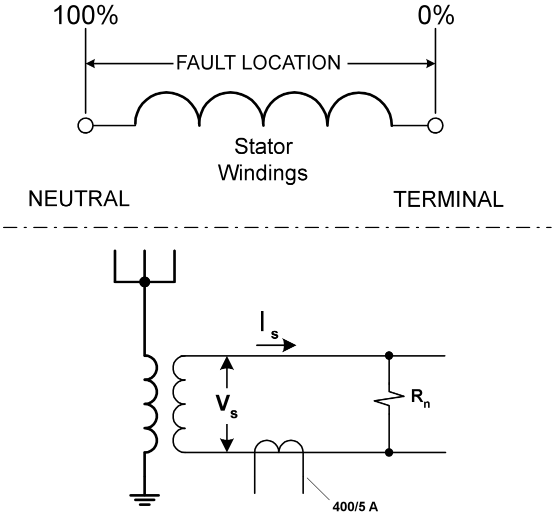

Fig. 3. Fundamental voltage across R_N as function of ground fault location

Fig. 4 shows the voltage and current measured by a 64S relay during start-up of a generator at a pump storage facility. Pump storage works as follows. A large body of water held in one reservoir runs downhill to another reservoir and turns a generator turbine to provide power during periods of high demand. The machine is operated as a motor during lightly loaded system conditions and pumps the water back up to the top reservoir. The machine is brought online and up to full speed via a back-to-back start from another running machine. Table 5 provides a description of each channel and the magnitude.

TABLE 4

FUNDAMENTAL VOLTAGE DROP ACROSS GROUNDING RESISTOR AND CIRCULATING CURRENT

Fault Location	V_S	I_S	I_S**/CTR**
100% (phase side)	110 V	(110 V)/0.32 Ω = 343.75 amps	4.297 amps
90%	99 V	(99 V)/0.32 Ω = 309.375 amps	3.867 amps
80%	88 V	(88 V)/0.32 Ω = 275 amps	3.438 amps
70%	77 V	(77 V)/0.32 Ω = 240.625 amps	3.008 amps
60%	66 V	(66 V)/0.32 Ω = 206.25 amps	2.578 amps
50%	55 V	(55 V)/0.32 Ω = 171.875 amps	2.148 amps
40%	44 V	(44 V)/0.32 Ω = 137.5 amps	1.719 amps
30%	33 V	(33 V)/0.32 Ω = 103.125 amps	1.289 amps
20%	22 V	(22 V)/0.32 Ω = 68.75 amps	0.859 amps
10%	11 V	(11 V)/0.32 Ω = 34.375 amps	0.430 amps
0% (neutral side)	0	0	0

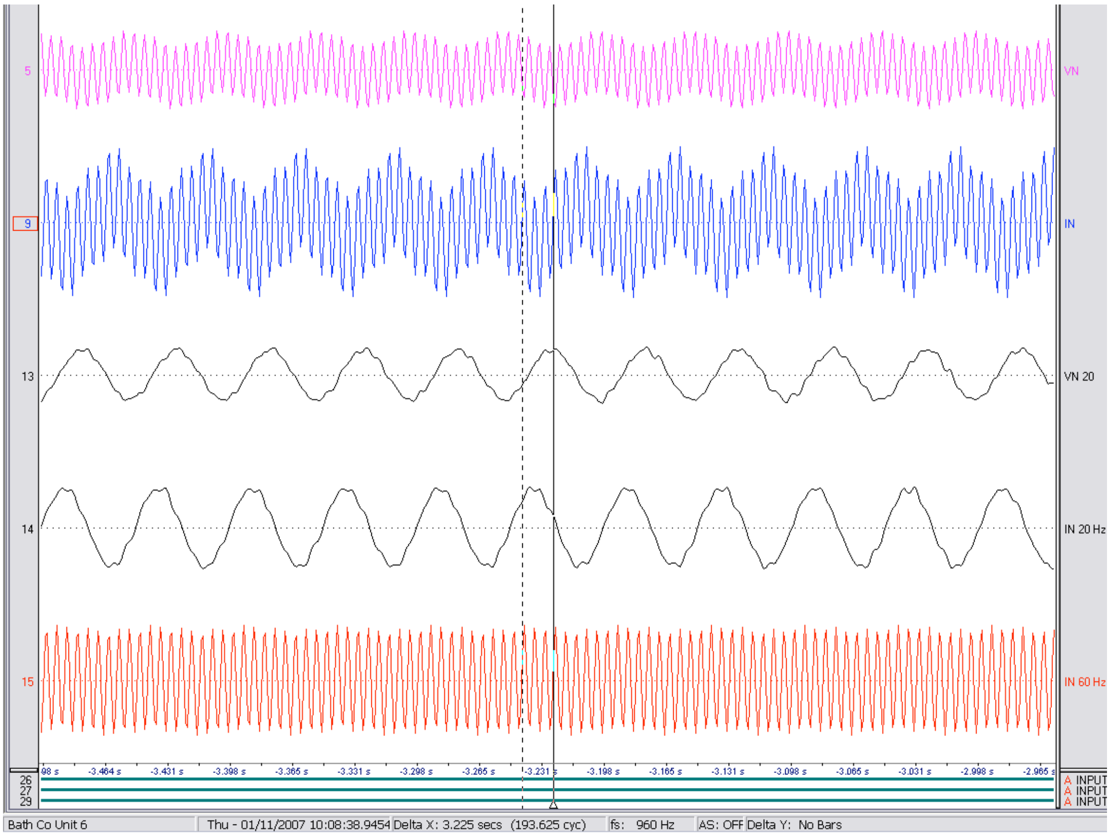

Fig. 4. Voltage and current measured by 64S relay during start-up

TABLE 5
CHANNEL DESCRIPTION AND MAGNITUDES

Channel	**Frequency**	**Magnitude**
V_N	Total	3.986 volts
V_N	20 Hz	98 mV
I_N	Total	68.550 mA
I_N	60 Hz	62.847 mA
I_N	20 Hz	3.253 mA

Under-frequency Inhibition: Use an under-frequency element that operates on the system voltage to block the 64S relay if nuisance tripping occurs during either startup or shutdown of the generator; that is, when the generator is transitioning through the lower frequencies. A typical under-frequency setting is 40 Hz (for both 50 and 60 Hertz power systems).

Commissioning Instructions

Figure X below illustrates how to configure the grounding network during initial commissioning. You can determine the total capacitance to ground and calculate the overcurrent pickup setting based upon these field measurements.

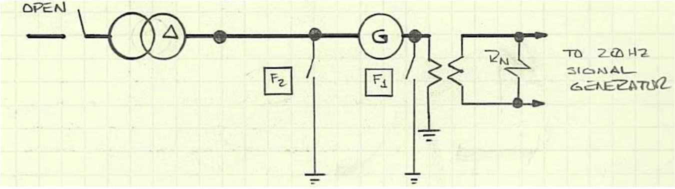

Fig. X. 20 Hz grounding network for Commissioning

Normal Operating Conditions

Configure the power system as follows:

- High side breaker is open
- Generator terminals are connected to delta windings of the generator step up transformer
- Switch F_1 is open
- Switch F_2 is open
- 20 Hz signal generator is online

Measure the following 20 Hz signals:

- V_N (neutral voltage)
- I_T (total 20 Hz current supplied by the signal generator)
- I_N (neutral current)

V_N and I_N are the 20 Hz signals applied to the relay inputs. Record I_N as $I_{N\ NOC}$. Modern numerical generator relays typically meter both of these values. These signals correspond to normal operating conditions. You can apply these values to equations (8) and (9) to solve for the total capacitance to ground (C_0).

Stator Ground Fault at Machine Neutral

Place a single line to ground fault at location F_1 and measure the 20 Hz I_N. This measurement corresponds to a short circuit applied at the neutral of the machine. Record this value as $I_{N\ F1}$.

Stator Ground Fault at Machine Terminals

Place a single line to ground fault at location F_2 and measure the 20 Hz I_N. This measurement corresponds to a short circuit applied at the terminals of the machine. Record this value as $I_{N\ F2}$.

Set the 64S overcurrent relay pickup such that it does not pickup during normal operation. The pickup should operate for a short circuit at either location F_1 or F_2. Set the pickup sensitive enough to detect a stator ground fault with up to at least 5,000 ohms primary of ground fault resistance if possible.

IV. CONCLUSIONS

This protection provides 100% coverage of the stator windings for ground faults including when the machine is off-line.

The total capacitance-to-ground of the generator stator windings, bus work and delta-connected transformer windings of the unit transformer is a very important factor and must be known to ensure the protection settings are correctly determined.

There are cases when it is hard to distinguish between normal operating conditions and an actual ground fault unless special steps are taken in the design of this protection. A good rule of thumb to decide if the real component of 20 Hz current is necessary is when C_0 is greater than 1.5 micro-Farads and the grounding resistor is less than 0.3 ohms secondary. Use the real component of the 20 Hz current measured by the relay for these cases.

The protection must reject fundamental frequency (50 or 60 Hz) voltage and current signals that are present at the relay measuring inputs during ground faults on the stator windings.

Use an under-frequency element that operates on the system voltage to block the 64S relay if nuisance tripping occurs during either startup or shutdown of the generator.

V. REFERENCES

[1] "The Art and Science of Protective Relaying" by C. Russell Mason, Wiley (1956), pp. 209 – 210.

VI. BIOGRAPHY

Steve Turner is a Senior Applications Engineer at Beckwith Electric Company, Inc. His previous experience includes working as an application engineer with GEC Alstom for five years, primarily focusing on transmission line protection in the United States. He also was an application engineer in the international market for SEL, Inc. again focusing on transmission line protection applications. Turner wrote the protection-related sections of the instruction manual for SEL line protection relays as well as application guides on various topics such as transformer differential protection and out-of-step blocking during power swings. Turner also worked for Progress Energy in North Carolina, where he developed a patent for double-ended fault location on transmission lines and was in charge of all maintenance standards in the transmission department for protective relaying.

Turner has both a BSEE and MSEE from Virginia Tech University. He has presented at numerous conferences including: Georgia Tech Protective Relay Conference, Western Protective Relay Conference, ECNE and Doble User Groups, as well as various international conferences. Turner is also a senior member of the IEEE.