PROTECTION CONSIDERATIONS FOR COMBUSTION GAS TURBINE STATIC STARTING

Working Group J-2 of the Rotating Machinery Subcommittee,
Power System Relay Committee

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Abstract-- **This paper was written by a Working Group of the IEEE Power System Relaying Committee to provide guidance to the industry to better understand the Combustion Gas Turbine (CGT) static starting process. This paper discusses the static start sequences, the categories of machine grounding used during static starting, short circuit characteristics of synchronous machines during static starting, and protection applications employed by the Load Commutating Inverter (LCI) controller and generator.**

Index Terms**—Combustion Gas Turbine (CGT), Load Commutating Inverter (LCI), Adjustable Speed Drive (ASD), Volts Per Hertz (V/Hz), Direct Current (DC), Root Mean Squared (RMS), Discrete Fourier Transformer (DFT), Current Transformer (CT), Voltage Transformer (VT)**

I. INTRODUCTION

The purpose of this paper is to provide a single document that can be used to address special protection requirements on combustion gas turbine (CGT) generators employing LCI static starting. This will address operational effects on instrument transformers and protection element application, functionality, and accuracy. Static starting of combustion gas turbines is accomplished by using an LCI, adjustable speed drive (ASD) system, to motor the synchronous machine and coupled turbine. The basic LCI static starting system consists of an isolation transformer, 6-pulse drive and controls, and isolation switches. Excitation to the field is automatically controlled to limit stator voltage to prescribed levels to maintain constant volts per hertz during the process in order to be synchronous with LCI frequency.

Figure 1 shows a plot of the static starting process of speed versus time for an example CGT. The process begins by operating the LCI to accelerate the machine from turning gear to purge speed. It typically takes 4.5 minutes to reach the purge speed of 0.3 per unit. Purging the compressor takes approximately 6 minutes. Next, the LCI is turned off and the machine allowed to coast down for about 3 minutes to about 0.14 per unit speed in preparation for firing the turbine. The LCI is operated during ignition, which takes about 2 minutes. Finally, the LCI accelerates the machine to full speed bringing the unit up to 0.9 per unit speed.

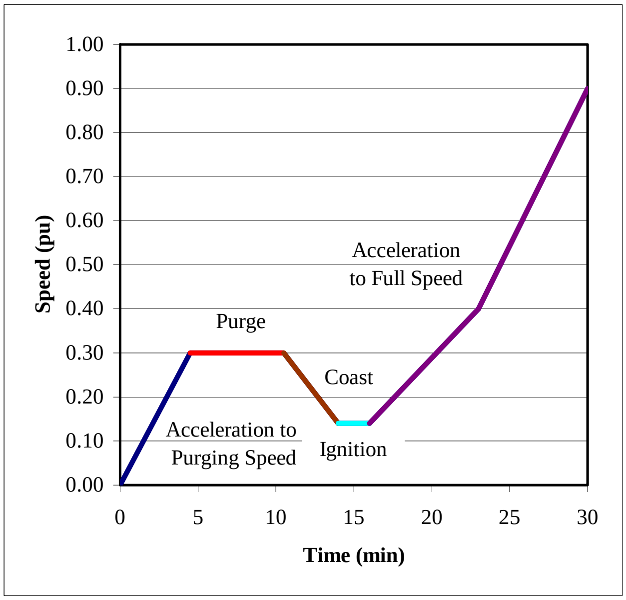

Figure 1, Static Start Sequence – Speed vs. Time

Figure 2 shows a plot of the static starting process stator voltage versus time for the example CGT. Closely controlled excitation is applied during the start up process to avoid saturation. Voltage is incrementally increased in conjunction with speed to limit machine volts per hertz to a maximum of about 0.77 pu.

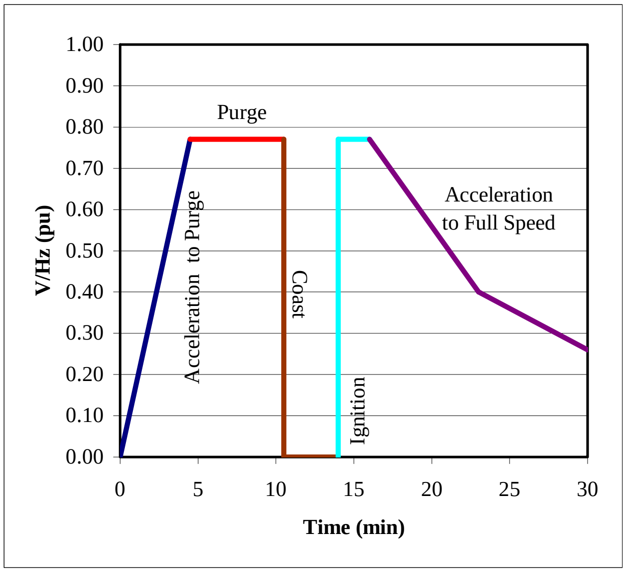

Figure 2, Static Start Sequence – V/Hz vs. Time

II. CATEGORIES OF MACHINE GROUNDING METHODS DURING STATIC START

A. High-Resistance Grounding with neutral grounding transformer

Grounding the neutral of a generator through a distribution transformer with a secondary resistor is common practice in North America. The resistance is typically sized to be equal to the total phase-to-ground capacitive reactance per phase, Xc, to avoid possible damage from high transient overvoltages that can occur from ferroresonance. The neutral resistance typically limits ground fault current to 3-25A or less. If this equipment is left in the circuit during static starting, a ground fault on the DC link of the static starter will cause DC current to flow in the primary of the distribution transformer with resultant quick saturation. On saturation, the DC current through the neutral is primarily limited by the transformer primary resistance. The distribution transformer's thermal capability will be exceeded if the fault is not removed. The transformer is less vulnerable than the grounded Wye PTs connected in the generator circuit, which have less capability to withstand DC. DC faults must be removed quickly and are detected by measuring primary DC current in the generator neutral.

B. High-Resistance Grounding with neutral resistor

Grounding the neutral directly through a resistor is a common practice outside of North America. Again, the object is to limit ground fault current to less than 3-25A. DC faults are detected by measuring primary DC current in the neutral.

C. Ungrounded

Generator static starting with the machine ungrounded is conducted by design by one manufacturer to eliminate the possible problems caused by a DC-link fault. The design switches the high-resistance neutral grounding scheme out of the circuit during starting, and uses open-delta voltage transformers for instrumentation. The rationale for this method is that an LCI DC-link reactor ground would saturate the neutral grounding transformer, wye-wye grounded voltage transformers, and to a lesser degree, the generator. The ungrounded generator and open-delta VTs will not provide a path to ground for DC current to flow.

III. SHORT CIRCUIT CHARACTERISTICS

Generator symmetrical short circuit current at no load can be determined by the equation:

$$I_{sc\,rms} = \frac{P}{\sqrt{3}V}\left[\left(\frac{1}{X''d} - \frac{1}{X'd}\right)e^{-t/T''d} + \left(\frac{1}{X'd} - \frac{1}{Xd}\right)e^{-t/T'd} + \frac{1}{Xd}\right]$$

where; *P* = three-phase rated VA, *V* = rated line voltage, *X"d* = per unit machine subtransient reactance, *T"d* = field short circuit subtransient time constant, *X'd* = per unit machine transient reactance, *T'd* = field short circuit transient time constant, and *Xd* = per unit machine synchronous reactance.

The expression 1/X"d represents 1.0 per unit voltage / X"d per unit in the equation. However, the stator will be subjected to less than 1.0 per unit voltage during the LCI Start sequence. Therefore, generator symmetrical short circuit current at static start can be determined by the equation:

$$I_{sc\,rms} = Ibase\left[\left(\frac{Vpu}{X''d} - \frac{Vpu}{X'd}\right)e^{-t/T''d} + \left(\frac{Vpu}{X'd} - \frac{Vpu}{Xd}\right)e^{-t/T'd} + \frac{Vpu}{Xd}\right]$$

The inductive reactance values will vary depending on frequency (speed) during start up. Generator reactances and time constants for a typical cylindrical rotor machine were used for this analysis. Those were as follows:

X"d = 0.135 per unit
T"d = 0.03 seconds
X'd = 0.215 per unit
T'd = 0.7 seconds
Xd = 1.91 per unit

Figure 3 shows a plot of the available initial RMS symmetrical short circuit current versus time during the static starting process for the example CGT. The available initial RMS symmetrical short circuit current for the example generator at rated speed, no load is 7.41 per unit. During the stages acceleration-to-purge, purge, ignition, and initial acceleration-to-full speed, the speed and voltage are controlled to maintain a constant volts per hertz level of 0.77 per unit. Thus, initial short circuit current at these stages is 77% of the 7.41 per unit at rated, or 5.7 per unit. Following the initial acceleration to full speed stage, the field will be excited to bring the generator voltage to the ceiling starting voltage (typically 25.6% of rated voltage). This voltage will be maintained while speed is increased throughout the remainder of this stage (see Figure 1), thus reducing the volts per hertz and available initial short circuit current to the minimum value of 1.9 per unit seen in Figure 3 at 90% speed.

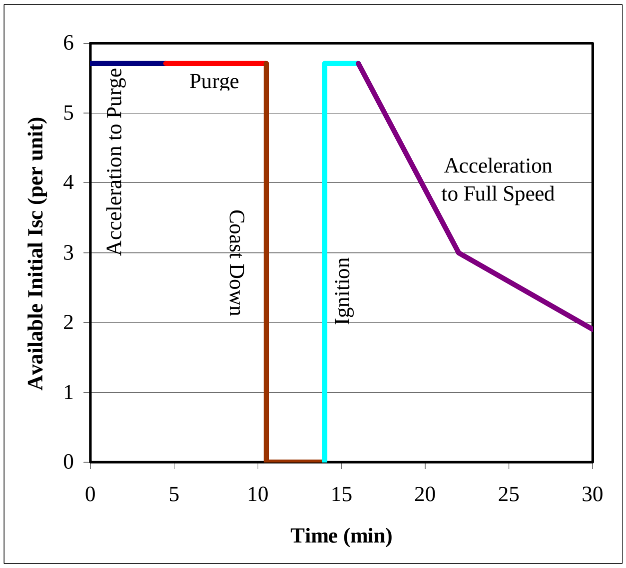

Figure 3, Static Start – Available Initial RMS Symmetrical Short Circuit Current vs. Time

IV. KEY PROTECTION ELEMENTS AND CONSIDERATIONS

CGT static starting protection encompasses three main components; the isolation transformer, the LCI, and the generator. The isolation transformer will be protected by traditional methods, and therefore, is not a focus of this discussion. Protection for the LCI and generator must be functional for the variable frequencies encountered during static starting.

A. Protection Used During Static Start

Typical generator protection may be limited during the initial starting sequence due to poor operation or non-response at low frequencies. Multifunctional digital relay functions may deviate outside of specifications due to inability to track the lowest frequencies. Thus, they should be evaluated for performance below their specified frequency range.

1. Low Frequency Response

This section explores the aspects of low frequency performance of protective relays and CTs. It will conclude that typical phasor measurement protective relay response time will remain proportional during its operating frequency range. In addition, dynamic simulations of CT performance during initial start up and rated speed are discussed with conclusions showing expected replication at starting frequency to be adequate for protective functions.

Many protection elements are designed to respond to the phasor components of the power system voltage and current. Typically, in a microprocessor-based relay, a discrete Fourier transform (DFT) calculates phasor values from samples of the voltage and current taken over a fixed period of time (DFT length). The DFT produces an accurate estimation of the fundamental component and rejects harmonics when taken over a full power cycle. If the DFT length does not match the power cycle then the measurement becomes less accurate. Figure 4 shows the magnitude response of a DFT when the DFT length is equal to the power cycle and when it is 110% of the power cycle.

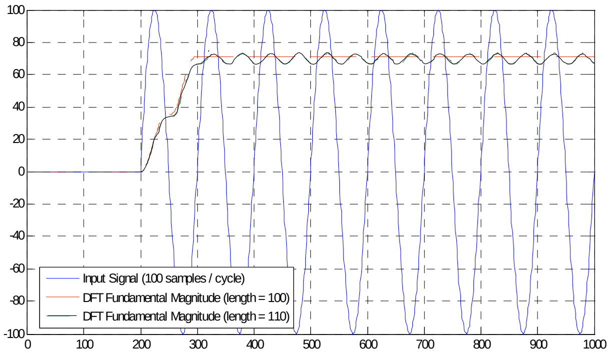

Figure 4, DFT Response

A limited number of protection functions are required during LCI starting such as overexcitation and overcurrent. Overexcitation derives its operating signal from the voltage magnitude and frequency. Similarly overcurrent uses the magnitude of the current. Some relays employ time domain RMS calculations to produce the operating signals for these functions. These calculations are not affected by a change in system frequency. Other relays adapt their phasor estimation algorithms to retain accuracy. Two approaches are generally employed to produce an accurate phasor estimation: One approach is to adjust the sampling rate of the relay in order to maintain a constant number of samples per cycle (frequency tracking). Another approach is to calculate the error introduced by the difference between the DFT length and the power system cycle and to compensate the measured phasors for this error. Although implemented differently, each of the three methods can produce accurate results.

The response time of protection functions that use phasor quantities is also affected during low frequency operation. This is due to the ramping effect of the DFT. For instance a particular protection function that takes 1 cycle to operate at 60 Hz will also require 1 cycle at 6 Hz. In real terms, the speed of operation is 10 times longer (166 ms) at 6 Hz. Protection functions with definite-time characteristics are further affected. A function with a definite time delay of 5 cycles will take 83 ms to time-out at 60 Hz and 0.83 seconds to time-out at 6 Hz.

At very low frequencies the instrument transformers and the internal magnetics of the relay will affect the accuracy of the voltage and current measurements. During a fault the increased magnitude and the offset in the current waveform will further degrade the measurement. However, during LCI starting, both the available fault current and the system X/R are a function of the operating frequency with the lowest values occurring at the lowest frequency. These factors act to reduce the measurement error. For example, Figures 5 and 6 show the results of a computer simulation fault at the terminals of a 38.4 MVA generator when the system frequency is 60 Hz and 18 Hz.

The machine was initialized at 1 pu speed and voltage for the first plot and 0.3 pu speed and 0.23 pu voltage for the second plot. All quantities are per unit and time is in seconds. A three-phase fault was applied at the machine terminals and the CT primary and secondary currents were captured. A generic Fourier transform was used to calculate the current phasor magnitude (shown in blue).

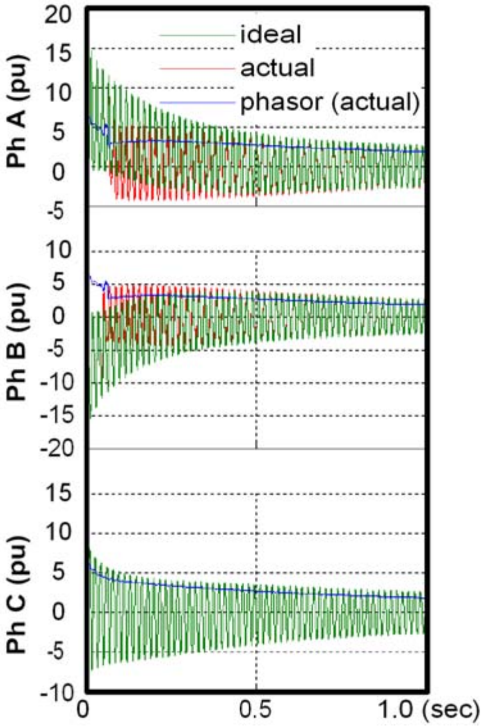

Figure 5, 3 Phase Fault, Speed=60 Hz, Voltage=1.0 pu

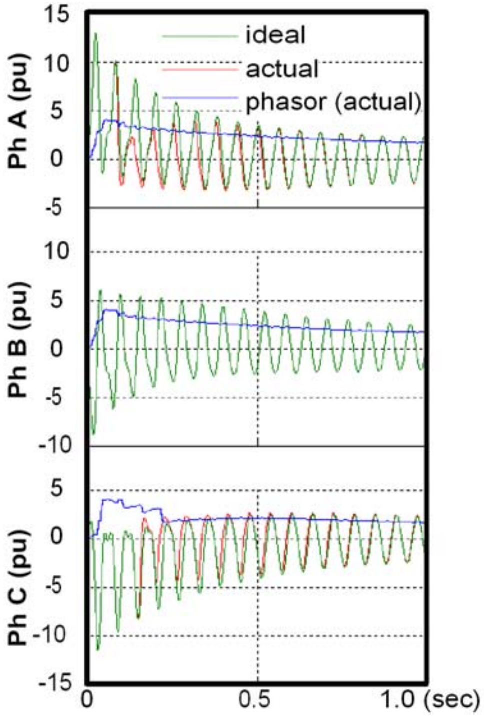

Figure 6, 3 Phase Fault, Speed=18 Hz, Voltage=0.23 pu

Note that for the 60 Hz case, in Phase C Ideal equals Actual current because there is no DC offset in the waveform and as a result no CT saturation. The phasor magnitude is decremented as expected for a synchronous generator. Phases A and B show CT saturation (green and red traces do not coincide). This causes a slight reduction in the phasor magnitude. In the 18 Hz plots, the peak value of the fault current is reduced somewhat due to the reduction in voltage. Phase B current is relatively symmetrical with no saturation occurring. The peak value of the phasor magnitude is also reduced because the instantaneous value decrements before the fourier ramps to its ultimate value. Saturation occurs this time in phases A and C but the degree of saturation does not differ significantly from the 60 Hz case. In general the transient response of the generator and its CTs are not adversely degraded at this frequency and should not create problems for relay settings calculations.

2. Specific Protection Applications

a. Differential

The generator is disconnected from the system and then connected to the static starting equipment for the start up sequence. Since the frequency will vary from very low to rated frequency during starting, the performance of a specific relay under low frequency conditions has to be considered. In addition the performance of CTs under low frequency conditions must also be considered. The differential protection may not be effective at low frequency or security may be an issue.

The static starter is often connected inside of the generator differential protection zone. With this connection, current from the static starter will be sensed by the neutral side generator CTs, but not the CTs on the system side of the generator circuit breaker or disconnect switches. This will result in some level of differential current being sensed by the differential relay during the static starting process. Different approaches have been used to deal with this, including using alternate relay settings during static startup to desensitize the differential relay (increasing pick up) or adding CTs on the output of the static starter to the generator differential zone. Another approach is to block the differential relay from operating during startup and rely on other protection, including that provided as part of the static starter control package.

The static starter may also be connected inside the overall differential zone. Similar approaches to dealing with the generator differential have been used to ensure security.

b. Phase and Ground Protection

Phase instantaneous overcurrent protection would be applicable to detect short circuits during startup. The pickup setting would have to be higher than the maximum stator current seen during the startup sequence.

Ground fault protection applications will depend upon the manufacturer. If the high-resistance grounding scheme remains intact during startup, then variable frequency voltage detection across the neutral resistor and neutral dc current detection methods could be used. If the generator is ungrounded during startup, then detection of ground faults is accomplished via the LCI controls.

c. Volts per Hertz

Volts per hertz protection specific to startup operations is required due to lower than rated stator voltages and variable frequencies.

B. Drive Mechanism Protection

Typically a number of protective functions are provided in the drive mechanism for Static Starting Combustion Turbines. These functions provide for the unique protection requirements for static starting from DC to rated frequency levels. Analog to digital conversion of the input currents and voltages are used in protection algorithms within the LCI controller to protect the drive components and machine. These input quantities are measured to detect an alarm, fault, or abnormal operating condition and initiate action such as an immediate shut down of the LCI starting process.

Figure 7 illustrates Drive Mechanism Protection examples of two manufacturer's approaches. Typically some form of Instantaneous, Inverse Time Overcurrent, and some form of Differential protection can be included. A ground fault detection system is generally implemented in the drive system that can be an active injection system. An undervoltage and overvoltage protection is also typically provided. Typically, drive system protection monitors input (source) and output (load) current and voltage, along with LCI, exciter, and machine operation. In some cases Volts per Hertz protection is included to insure proper flux levels are maintained. Supply transformer protection can also be included. Protective functions in Protective Zones 2 and 3 are accomplished by analog to digital conversion of current and voltage, then measurement by comparator against specific standards.

Manufacturer A protection is shown on the left side of the schematic. It incorporates overcurrent and thermal protective relays for the transformer in Protective Zone 1, and multiple protective functions in the drive control for Protective Zones 2 and 3.

Manufacturer B protection is shown on the right side of the schematic.

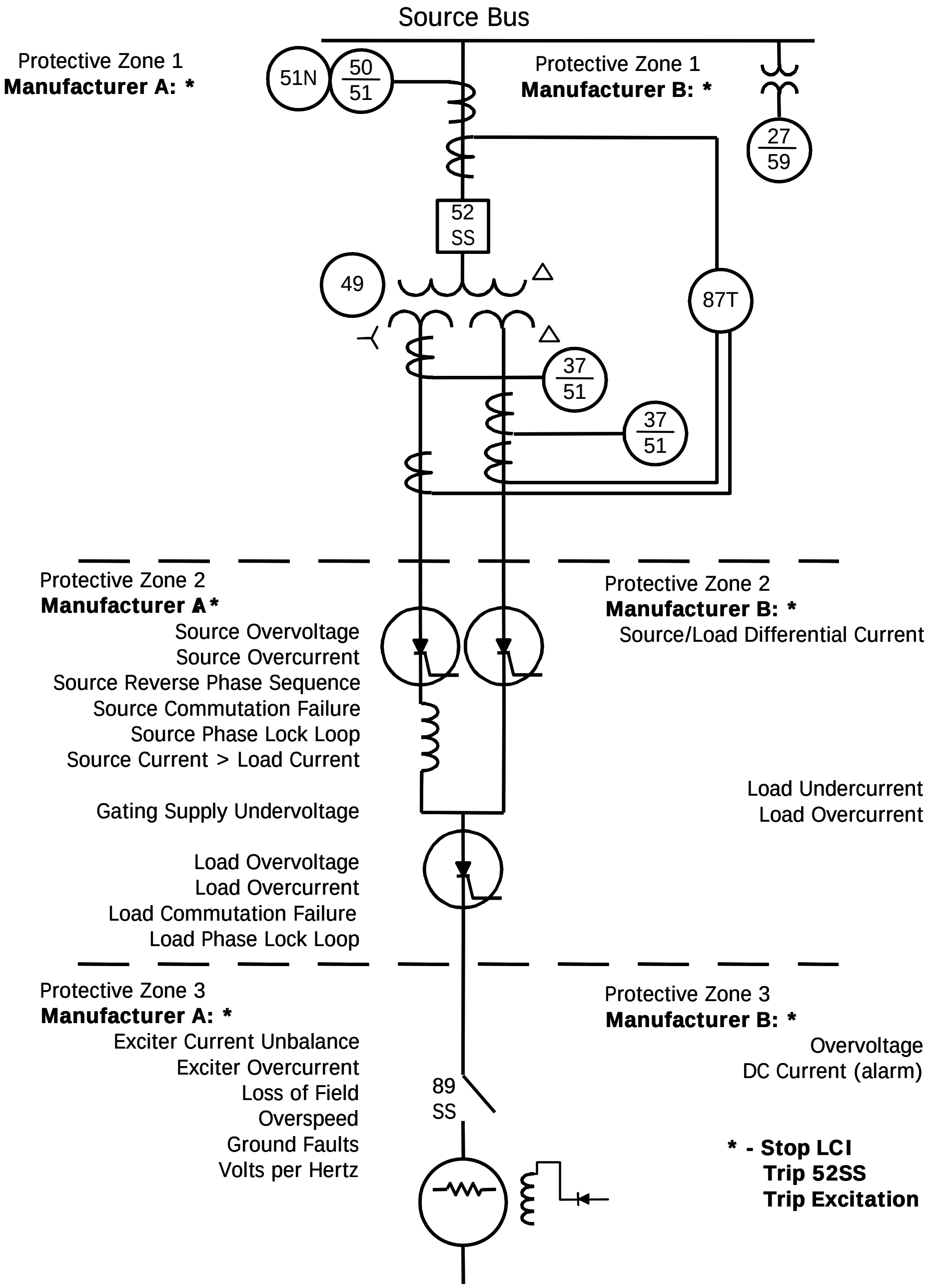

Figure 7, Drive Mechanism Protection - Manufacturers A and B

C. Generator Protection

Figure 8 illustrates generator and GSU protection schemes for Manufacturer A. Note that during LCI Start, the generator circuit breaker, 52, is open, and the LCI disconnect switch, 89-SS, is closed. LCI start is conducted with the generator ungrounded and neutral grounding transformer disconnect switch 89-DS open. 87GT requires special consideration during start up. Differential current pickup should be adjusted to accommodate the maximum LCI start current from the generator neutral CTs.

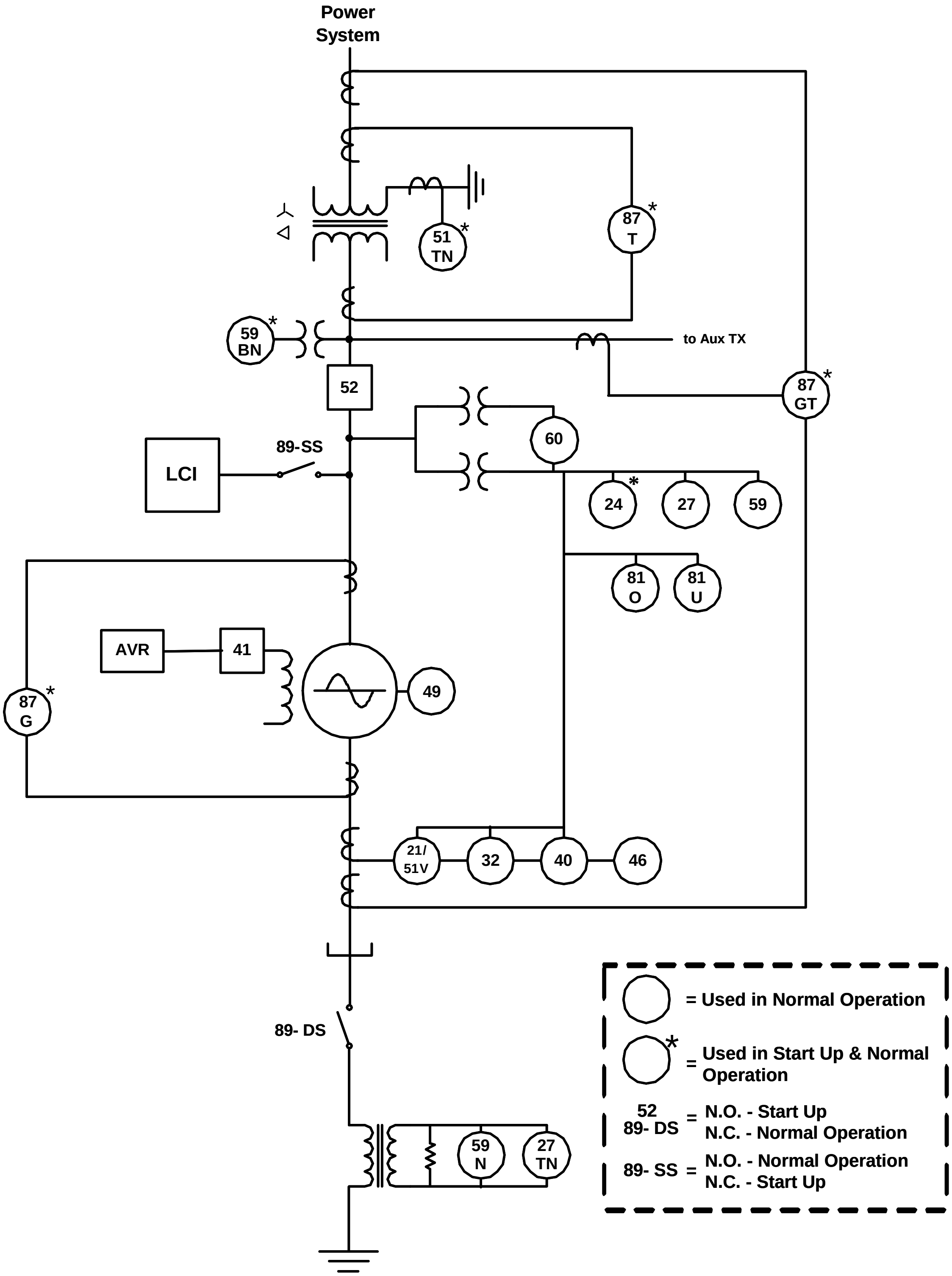

Figure 8, Generator Protection: Manufacturer A

Figure 9 illustrates generator and GSU protection schemes for Manufacturer B. Note that during LCI Start, the generator circuit breaker, 52, is open, and the LCI disconnect switch, 89-SS, is closed. Manufacturer B LCI start is conducted with the generator grounded and neutral grounding transformer disconnect switch 89-DS closed. 87GT and 87T require special consideration during start up. Differential current pickup should be adjusted to accommodate the maximum LCI start current from the generator neutral CTs.

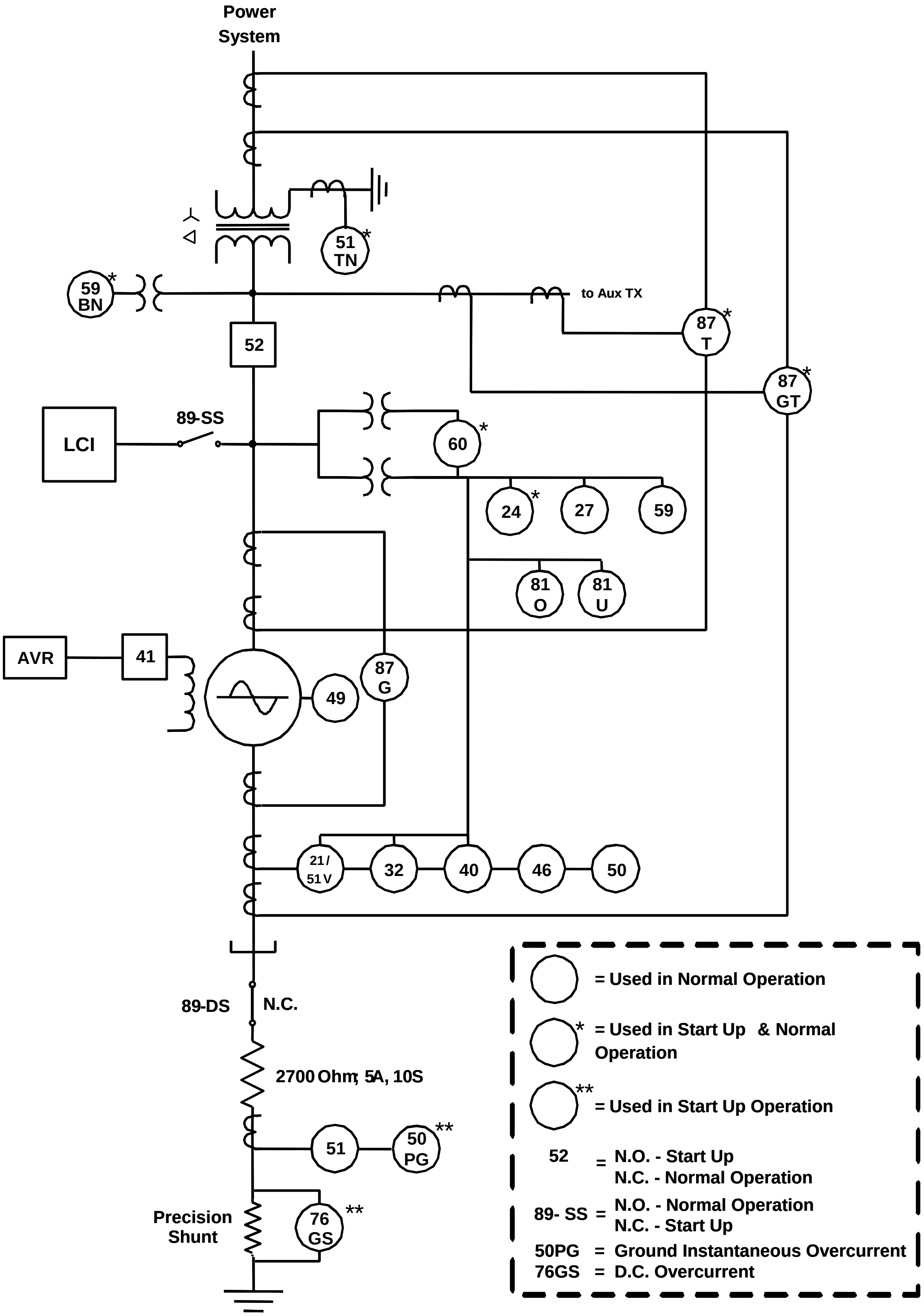

Figure 9, Generator Protection : Manufacturer B

V. SUMMARY

In closing, the topics discussed in this paper provide the protection engineer with an understanding of the Static Start process for Combustion Turbine driven generators. The paper addresses in detail the sequence of events and starting process details. Salient points for application consideration such as generator grounding, short circuit characteristics during static start, and key protection elements are presented. Within protection elements considerations the following are discussed; low frequency response of CTs and relaying, protection application, and drive mechanism protection.

Two manufacturer's schemes are presented as examples in the paper as well as a generic protection system one-line. It is recommended that all of these points be given careful consideration and that the static start and generator manufacturer is included when developing the static starting protection scheme for their system due to the specific differences between one manufacturer and another. The C37.102 "IEEE Guide for AC Generator Protection" as well as other pertinent industry guides should be reviewed for further details.