MULTIQUIP

Generator Motor Starting

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Generator Motor Starting

Sizing generators in today's robust rental equipment market can be complex and complicated. This is especially true when sizing generators to supply power for large inductive motors.

This short paper will address motor basics, starting current, the impact high transient current has on a generator and the important role transient reactance plays in estimating the generator size in the absence of generator performance data. This paper was written for rental equipment technicians for informational purposes only.

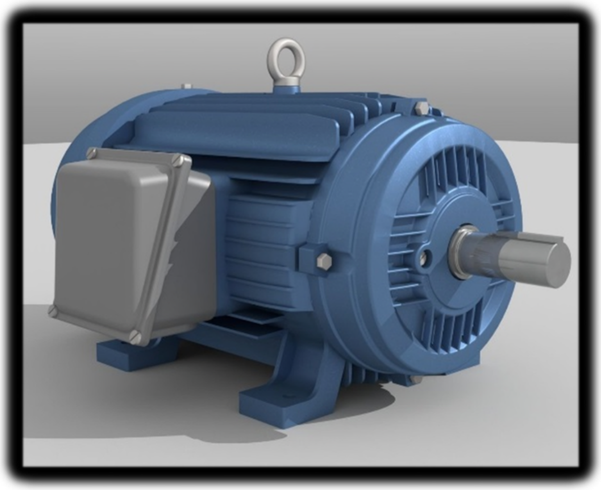

Figure 1# Inductive Motor

Basic Inductive Motor

Let's begin with a common generator rental application, running large inductive motors. These motors draw high in-rush current when started at full rated voltage applied directly to the motor terminals. This type of starting method is commonly referred to as direct online (DOL) or across the line starting. High in-rush current during initial starting can cause current spikes four to eight times the motor full-load current and remain high until the motor reaches approximately 75 to 80 percent of it rated speed.

Three-phase inductive motor with DOL starting are the most common and economical motors used in industrial settings. The DOL starting method is simple, full voltage is applied across the stator windings, the maximum torque is developed, acceleration is fast and heat inside the windings is low. The main limitation of DOL starting method is the initial heavy inrush current, which may cause severe voltage disturbances to other connected loads and to external power sources such as generators.

The stator of a three-phase inductive motor consists of overlapping windings offset by an electrical angle of 120 degrees. When an inductive motor is at rest or stationery when rated voltage is applied to it terminals only a small amount of resistance and reactance oppose the flow of current. This low impedance creates high inrush current and with the degree of separation in the windings a rotating magnetic field (flux) is created within the stator, similar to a transformer. This rotating magnetic flux cuts the rotor conductor across the air gap which induces electromotive force (EMF) according to Faraday's laws of electromagnetic induction. The rotor conductors are shorted by either end rings or low external resistance which causes a large instantaneous current flow.

The flow of current in the rotor explained by Lorenz' law opposes the induced EMF which creates mechanical force causing the rotor to rotate in the same direction as the stator's rotating magnetic flux. As rotor speed increases the current flow decreases and continues to decrease as the rotor accelerates toward the synchronous speed of the rotating magnetic flux of the stator. If the rotor speed matches the speed of the stator, no current will flow or be induced into the rotor. This explains why rotor speed is always slightly less than synchronous speed. The difference between the two is commonly referred to as "slip". [1] This operating principle of the inductive motor is why a three-phase motor is often referred to

[1] Simpson, C. (1992) Introduction to Electric Circuits and Machines

as asynchronous machine because of the relative speed difference between the stator and the rotor.[2]

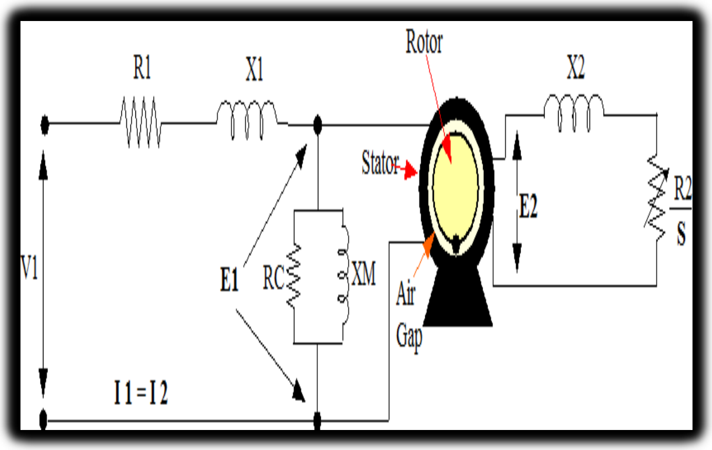

Figure 2# Equivalent Circuit of 3-Phase Induction Motor

Equivalent Circuit Example

An induction motor is similar to a transformer from an equivalent circuit perspective. The stator windings correspond to the primary circuit and the rotor windings corresponds to a short-circuited secondary circuit.

Figure 2# shows the equivalent circuit for 1- phase of an induction motor. V1 is the applied voltage supplied to the stator terminals. R1 represents the resistance in the stator, X1 represents the stator leakage reactance (flux that does not link with the air gap and the rotor). The magnetizing reactance required to cross the air gap is represented by XM and core losses (hysteresis and eddy current) by RC. For the rotor side, E2 is the induced EMF in the rotor and is affected by the slip (as the rotor gains speed, slip reduces and less emf is induced). The rotor resistance and reactance are represented by R_2 and X_2; with X_2 being dependent on the frequency of the induced EMF.[3]

Compared to a transformer the motor has an air gap whereas a transformer has a core. The magnetizing current as represented by XM is larger than that of a transformer, motor is about 30 to 60% of the rated current whereas a transformer is about 1 to 4% of the rated current of the transformer.[4] The stator and rotor are distributed around the periphery of the air gap versus concentrated on a core as in a transformer, so the reactance of a stator and rotor are larger compared to a transformer. Transformer is all electrical versus a motor, input is electrical, but the output is mechanical. [5]

The motor's rotor voltage E2, reactance X2, and frequency are proportional to the slip. Varying resistance R2 represent slip. The whole of the induced EMF in the rotor windings is used to setup the initial circulating current which cause the rotor to rotate. As the speed of the rotor approaches the synchronous speed of the stator the current is reduced which means R2/S increases in value with speed. As you can see by the equivalent circuit illustration the start-up current in an inductive motor is very large due to the small amount of resistance and leakage reactance of the circuit. The current is large to create the required magnetizing current in the stator to cross the air gap to induce the required current in the rotor to start the rotation of the motor from a rest position. Based on the illustration, sag in applied voltage has a direct impact on the required magnetizing current, induced EMF and the speed/time curve run-up to synchronous speed. Rotor Circuit, current I2 is given by:

$$I2 = \frac{E2}{\sqrt{\left(\frac{R2}{S}\right)^2 + (X2)^2}}$$

If the values were known current could be calculated by reducing the circuit to an equivalent impedance: (Z eq)

$$Is = \frac{V1}{Zeq}$$

[2] Simpson, C. (1992) Introduction to Electric Circuits and Machines
[3] McFadyen, S. (2014) Induction Motor Equivalent Circuit
[4] McFadyen, S. (2014) Induction Motor Equivalent Circuit
[5] McFadyen, S. (2014) Induction Motor Equivalent Circuit

$$Z_{eq} = Req + \frac{R^2}{S} + Xeq$$

From this equation, as the rotor speeds up (slip reduces), the circuit impedance increases and stator current decreases.

Locked-Rotor Current

Locked-Rotor current/torque is the torque the motor develops when it starts at rest or zero speed. The only opposition to current flow when a motor is at rest is a small amount of resistance and reactance which causes a large amount of current to initially flow when rated voltage is connected to the motor terminals. This very large inrush current demand during initial starting can exceed 4 to 8 times the running current of the motor and it decreases as the motor torque accelerates. The inrush current amounts to a short-circuit current (hence the term locked-rotor current). The term Locked-Rotor can apply to when the motor is started at rest or stalled due to a blockage or jammed so the motor can't rotate. If the motor becomes jammed, no counter-electromotive force (CEMF) will be produced in the windings and will result in a decrease in impedance to a point that it effectively becomes a short circuit. If current isn't removed this can result in overheating and cause damage to the motor windings.[6]

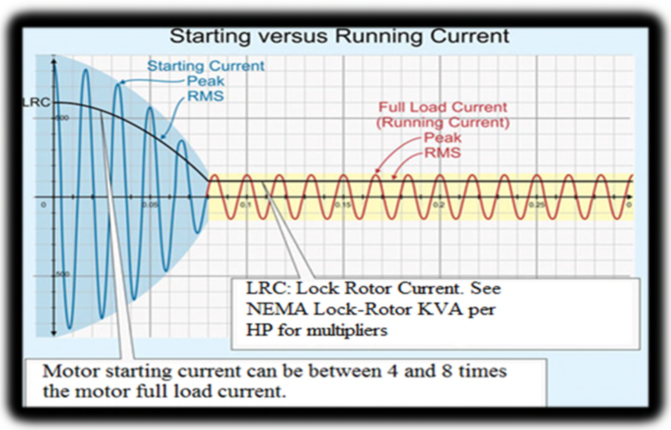

Illustration provided coustey of Mike Holt Enterprise

Figure 3# Starting Current versus Running Current

Figure 3# is an example of starting/locked-rotor current versus running current.

Understanding Locked-Rotor current is important in estimating voltage dip at start-up. Locked-rotor current is also used to ensure overcurrent protection is sufficiently sized to endure the high inrush current during motor starting.

Locked-Rotor Current Code Letters

Letter Designation	KVA per Hp*
A	0 - 3.15
B	3.15 - 3.55
C	3.55 - 4.0
D	4.0 - 4.5
E	4.5 - 5.0
F	5.0 - 5.6
G	5.6 - 6.3
H	6.3 - 7.1
J	7.1 - 8.0
K	8.0 - 9.0
L	9.0 - 10.0
M	10.0 - 11.2
N	11.2 - 12.5
P	12.5 - 14.0
R	14.0 - 16.0
S	16.0 - 18.0
T	18.0 - 20.0
U	20.0 - 22.4
V	22.4 and up

Figure 4# NEMA Locked-Rotor Codes

National Electrical Manufacturers Association (NEMA) has established a design letter code that defines the locked rotor current kVA on a per horsepower basis. The letter code covers the characteristics of torque and current of the motor. The letter code consists of letters from A to V. Figure 4# shows the values of locked rotor current kVA per hp for NEMA designed motors. The NEMA Code Letters are referenced in Table 430.7(B) of the National Electrical Code.

[6] Holt, C.M. (2017) Illustrated Guide to Understanding the National Electrical Code. Part 1. Articles 90-480.

The NEMA Locked-Rotor code designator should be located on the motor data plate as required by the National Electric Code (430.7(B)), see Figure 5#.

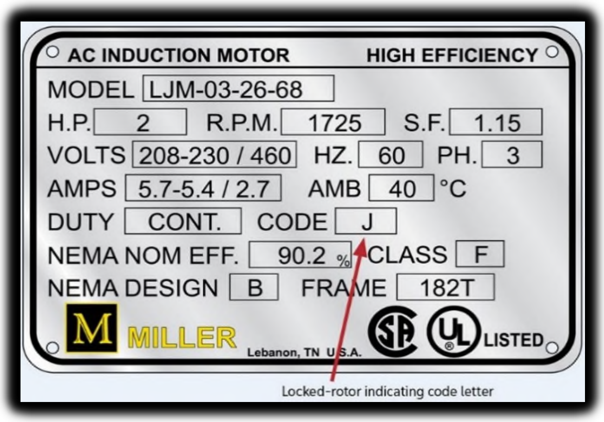

Figure 5# Locked-Rotor Designation

Do not confuse the NEMA Locked-Rotor code and design letters. The code letter refers to the ratio of locked rotor kVA to HP, whereas the design letter refers to the ratio of torque to speed.

Other Motor Considerations

When full rated voltage is applied to the motor terminals it's critical the motor reach it operating speed as quickly as possible, large sags in applied voltage and frequency can cause the motor time curve to speed to increase therefore, causing current to remain high longer than expected causing additional heat and mechanical stress on system components. Voltage and frequency sags can also affect the motor's supply contactor causing it to prematurely open or fail. Most motor contactor coils have a drop-out voltage rating of approximately 70-75% which means the voltage dip should not exceed 25 to 30%. Excessive voltage dips or sags can cause contactors to chatter or arc leading to failure.

When motors are started on utility power the start-up current will only cause a minor voltage dip because the utility is a more robust power source, typically referred to as an "infinite bus". However, when a large motor is started on a generator, the high start-up current can result in high voltage and frequency dips or sags which can inhibit the motor from reaching its optimum operating speed causing additional heating in the motor, generator windings and cause power quality issues with other connected loads.

When a motor is supplied power from a generator, the high transient starting current creates a complex interaction between the motor and several generator components such as the alternator, engine, automatic voltage regulator (AVR), excitation system, and engine governing system. All the components must properly interact to minimize the voltage dip or sag the high starting current has on the system and other connected loads.

Generator Behavior & Voltage Dip

During starting, kVA demand on the alternator is high but the actual kW load demand on the engine is lower due to a low starting power factor of the motor. Generally, the starting power factor of a motor is very low in the order of 0.25 to 0.5 and increases during the run-up period to reach its peak just before normal operating speed. Thereafter, it drops very rapidly at synchronous speed. The running power factor or full-load power factor is generally in the order of 0.8 to 0.9 and of course is always lagging. When the load on the motor is reduced its power factor falls. The active power requirements during run-up is the product of kVA and the power factor. The rising power factor during the run-up or starting period means the peak power occurs at approximately 80% of the motor speed and the current is in the order of 3 to 3.5 time the name plate rating of the motor .[7]

Several variables play a role in generator response to an instantaneous inrush current. Variables that effect generator performance during sudden load changes can include but are not limited to alternator capacity,

[7] Mahon, J. (2004) Diesel Generator Handbook. Elsevier, Butterorth-Heinemann, Burlington, MA

impedance/reactance, voltage regulation system, excitation system, alternator heat rise, frequency, engine Hp, type of turbo system (turbo lag), type of fuel system, engine control and governor system. All of the items can have an impact on percentage of change and time of recovery/overshoot in both frequency and voltage.

Another consideration is emission tier level and whether the engine utilizes a diesel particulate filter or not which in most cases can have an indirect impact on engine transient response.

When a sudden load is applied to a generator depending on the magnitude of the load the engine will slow resulting in both a frequency and voltage dip. The initial voltage dip or sag is a function of the generator sub-transient and transient reactance. Recovery to nominal voltage is heavily dependent on the generator and voltage regulator driving the voltage back up to it nominal operating voltage.

One of the most important components is the excitation system. If the excitation system responds to quickly or too stiff it can overload the engine when large transient load changes occur. In general, the generator must recover voltage to at least up to 90% of rated voltage by few cycles, if it doesn't or the recovery is prolonged heavy voltage and frequency dip may occur. [8]

Typically, generator sets will utilize either a Shunt Excitation system or a Separately Derived Excitation system. A Separately Derived excitation system typically referred to as a pilot magnet generator or permanent magnet generator (PMG). The PMG system are independent of the load and supply the automatic voltage regulator (AVR) with clean input power, helping make the AVR virtually immune to non-linear loads. Another type of input excitation system is auxiliary windings such as the open delta windings located in the stator separate from load windings with the sole purpose of suppling input voltage to the AVR.

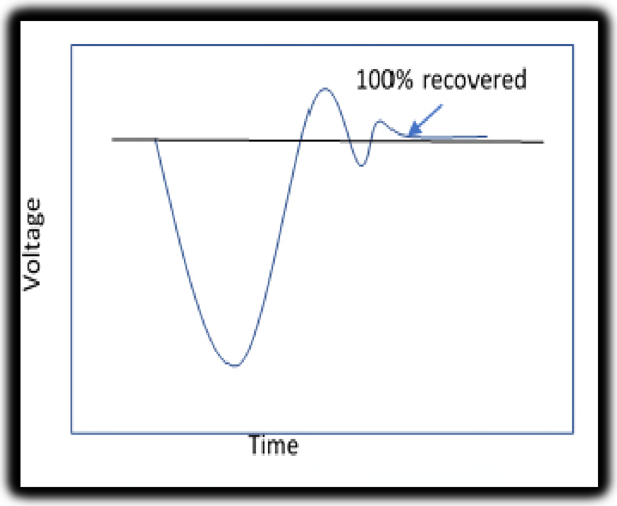

Figure 6#. Voltage dip example

The AVR monitors voltage/frequency then reacts to frequency dips or lags by aiding frequency recovery through limiting or even reducing excitation as a function of frequency. When frequency dips below a predetermined threshold as a result of a heavy instantaneous load change on the engine the regulator reduces generator voltage and in turn the kW load by the square of the voltage which allows the frequency to recover more rapidly and, at the same time, regulates voltage recovery to minimize voltage overshoot. The AVR also aids the generator to sustain fault current for a longer time period allowing downstream protective devices to operate. 300% fault current for 10-seconds is typical performance. Figure 6# shows the typical voltage effects on a generator from a heavy load change.

The amount of instantaneous load a generator can handle, and the overall severity of the voltage dip is primarily dependent on the reactance of the generator and the excitation system. Reactance is the opposition to AC current flow similar to resistance in a DC circuit and is used to describe the behavior of a generator during certain operating events. Transient

[8] Kirar, M.K., & Agnihotri, G. (2013) Emergency Generator Sizing and Motor Starting Analysis.

reactance (X'd) is used in motor starting calculations, lower X'd results in higher motor starting (i.e. lower voltage dip). Transient reactance generally ranges between 0.13 - 0.25pu for mid-range generators. Sub-transient reactance (Xd") is normally used in short circuit and arc flash calculations (lower the Xd" the higher the short circuit current. Sub-transient reactance ranges from 0.6 to 0.26pu. Generally, the effective time for sub-transient reactance is 0 to 6 cycles whereas, the effective time for transient reactance can be 6 cycles to approximately 5 seconds. Figure 7# shows the different regions of reactance.

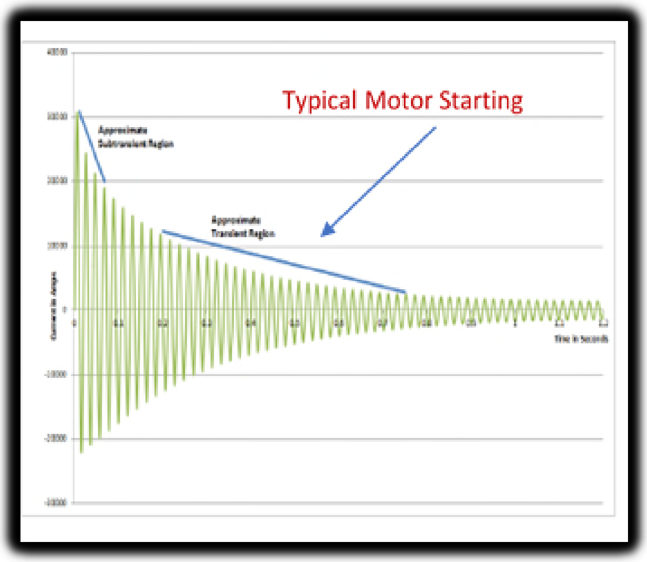

Figure 7# Region of Reactance

Generator Sizing for DOL Motor Starting

Many articles have been written about motor starting, and controversies always emerge over what is considered as an acceptable means of calculating generator motor starting capacity and voltage dip, which varies greatly between generator manufacturers.

Complicating the task of generator sizing for motor starting is the lack of a single standard that can be used to evaluate generator capability or validate its performance behavior during heavy transient load changes. The industry currently depends on the general evaluation of the alternator published by the National Electrical Manufacturers Association (NEMA) MG-1, part 32 requirements. NEMA as part of the MG-1 requirements refer to the manufactures for actual published generator performance curves which can vary greatly.

Regardless of the marketing tactics manufactures use to bolster the motor starting capabilities of their generators the instantaneous load can't exceed the generators load capabilities or damage may occur. The reactance of the generator is a very important indicator of the generator capability and the severity of the voltage dip it may experience during sudden load changes. Transient reactance provides an agreed method and consistent way to calculate a generator load capability however, caution should be exercised because using reactance as the sole means of calculation can be overly aggressive for some applications and produce an adverse effect on other connected loads.

The sub-transient reactance is generally used to calculate short circuit current, when a fault occurs, the current will rise quickly and then fall. As stated before the transient reactance region of the reactance curve is typically used to estimate motor starting and voltage dip.

NEMA MG-1 32.18.5.3 establishes a means of estimating the voltage dip based on the generator unsaturated transient reactance and ratio of rated kVA versus applied kVA.

Voltage Dip Equation :

$$\Delta V = X'd / (X'd + c)$$

ΔV is the estimated voltage dip

X'd is the per unit unsaturated transient reactance

C is the ratio (generator rating (kVA) / Impact or applied load (kVA)

See Figure 8# for and example of how the equation is expressed.

Voltage dip equation per NEMA MG-1, 32.18.5.3

$$\text{Voltage Drop} = \frac{X'd}{X'd + \frac{\text{Rated KVA}}{\text{Starting KVA}}}$$

X'd = unsaturated transient reactance, per unit

Figure 8# Example; NEMA Voltage Dip Equation

The equation shows that for a given machine rating (same kVA, same voltage, and constant frequency), lower the X'd, the lower the amount of voltage dip for an applied load.

Please note, the NEMA MG-1 equation is aggressive and based on transient reactance rather than sub-transient reactance plus it assumes frequency is constant throughout the starting cycle which is unlikely due to the magnitude of the kW load applied to the engine. The equation does not take the place of manufacture performance data but in the absence of manufacture data the equation could be used as a quick estimation since no other standards exist.

The magnitude of the voltage dip at the generator terminals following a sudden load change is a direct function of the generator sub-transient and transient reactance. Using Lock-rotor kVA per hp as the applied load, using the NEMA Voltage dip equation we can estimate the generator size based on an expected voltage dip.

NEMA MG-1 Equation : ΔV = X'd / (X'd + C)

Where X'd is unsaturated transient reactance and C is the ratio: Generator Rating (kVA) / Load imposed (kVA).

Example:

Hp x NEMA locked-rotor code, kVA per hp = SkVA,

(load (SkVA) / ΔV) – load (SkVA) = load x X.'d = Generator size in kVA

Load Data: 100hp, NEMA code G, 480V, 3-PH Motor, DOL starting method, voltage dip 25%, X'd assumed 0.17pu

100hp x 6.29 =629SkVA

(629 / .25)-629 = 1887, 1887 x 0.17 X'd = 320.7 kVA

NEMA MG-1 Voltage Dip Equation

$$\frac{0.17\,X'd}{0.17X'd + \frac{320kVA}{629SkVA}} = 0.250 \times 100 = 25\%\ \Delta V$$

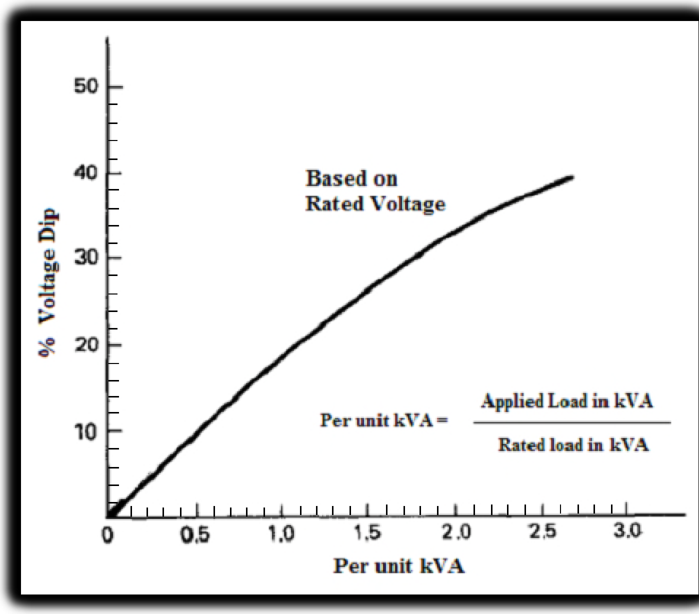

Figure 9# Conservative Curve (Rule of Thumb)

Figure 9# is a conservative starting curve or rule of thumb that could also be used as a quick estimation.

100hp, code H motor, DOL starting, 480V, three Phase. Code H = 7.10kVA per hp, 100hp x 7.10kVA = 710SkVA

Generator used is a 400kVA

710SkVA /400kVA = 1.77, Based on the curve the generator would experience approximately a 30% voltage dip based on the curve.

Another consideration is transient reactance changes when there is a voltage deviation from machine rated

voltage. The per unit reactance value changes inversely (rated volts down, reactance up) with the square of the voltage ratio if the kVA rating remains the same.
Example:

Rated generator voltage 240/480, transient reactance X'd is 0.17 pu. Voltage adjusted to 416V

$$(480\ /\ 416)^2\ X\ 0.17pu\ X'd = 0.226pu$$

Another math expression that may be helpful based on the NEMA equation as a quick estimation is listed below which uses motor kW instead of hp but it yields the same results when applied.

Denyo Motor starting equation:

$$\boldsymbol{PG = \frac{X\,d'(1 - \Delta V)}{\Delta V} x\ Pm\ x\ \beta\ x\ C\ \ (kva)}$$

PG: Generator capacity (kVA)

Xd': Generator transient reactance (generally 0.15 - 0.30)

ΔV: Momentary voltage dropping rate at start-up (generally 0.25-0.30)

Pm: Motor output (kw)

β: Motor starting input in kVA per kW (generally 6 – 9)

C: Coefficient depending on starting method (Direct Across the Line = 1, Wye-Δ = 0.67)[9]

Hp x 0.746 = kW, since the formula uses kw instead of hp it makes sense to convert the locked-rotor kva per hp to kva per kW = Locked-rotor kVA/0.746.

Denyo's math expression works the same as NEMA formula for voltage dip.

Example: 100hp, code G, 480V, 3-ph.

100 x 0.746 = 74.6kw, code G = 6.29 LRkVA per hp. (6.29/0.746)= 8.43 kVA per motor kw

X'd = 0.17pu, ΔV = 25%, β = 8.43, Pm = 74.6 kW

$$\frac{0.17X'd(1 - 0.25\ \Delta V)}{0.25\Delta V} \times 74.6\text{kW} \times 8.43\beta \times 1\ \text{C}$$
$$= 320\text{kVA}$$

The MQ Power Advantage

MQ Power manufactured alternators have excellent heat rise ratings and utilizes robust multiple output auxiliary windings wound in the stator core that are independent of the load winding to provide clean input power to the AVR. This robust "Separately Derived Excitation" system provides a high degree of immunity from the effects of non-linear loads and is specifically designed to endure the harsh and ever-changing rental environment.

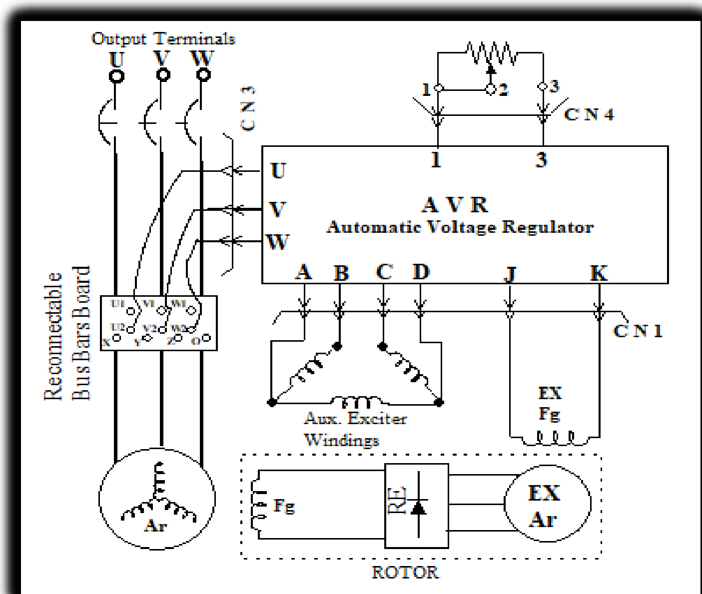

Figure 10# Open Delta Exciter System

More specifically the auxiliary exciter windings are coupled to one another in a three-phase series connection or open-delta with two open ends. See Figure 10# for an illustration of the open delta exciter system. The four terminal points of the windings connected to the AVR allow for automatic

[9] Denyo Handbook (2007) Sales Handbook, Page 17, Denyo Company, LTD., Tokyo, Japan

switching between the output points of the open delta exciter winding to provide current support to the field windings as load demand on the generator changes. This multiple output configuration allows the AVR to utilize the first field harmonic to generate power for normal operation and responds to transient loads and motor starting inrush current by utilizing the zero-phase component having the third harmonic obtained through the open ends of the series connected windings. The employment of the zero-phase component for field control make it possible for the AVR to have excellent response to motor starting and short-circuit faults beyond the standard of 300% for 10 seconds.

The excitation characteristics of the open-delta auxiliary winding coupled with the patented heavy-duty construction design AVR creates a robust system of transient load control and quicker recovery. The AVR utilizes three-phase voltage sensing for generator output monitoring. The sensing leads are center tapped at the reconnect board (180kVA and above) or selector switch (150kVA and below) so there is no operator interaction with the AVR required when switching from 240V to 480V.

The advantage of the use of the three-phase multiple output open-delta auxiliary windings compare to the use of a PMG system, Simply, it's a more robust and durable system for the harsh mobile/rental environment and has an extremely low incident rate whereas the PMG is an add-on systems available at an additional cost. The add-on PMG system increases the weight and length of the alternator and is less robust and durable in the everchanging harsh rental environment.

In addition to the robust excitation system MQ Power alternators have internal winding taps to provide true 120V at the convenience receptacles without the use of an additional transformer when the generator is operating at either 240 or 480 volts.

Summary

Sizing generators for instantaneous load changes such as "Direct across the line" motor starting can be a challenge especially in harsh rental environments. Accurate sizing of a generator set requires consideration of initial voltage dip, and recovery of the nominal voltage delivered to the load to at least 85 to 90% of nominal voltage as the motor is accelerating, and the ability of the generator set as a system to pick up the kW load demand applied.

This requires several components such as the alternator, excitation, automatic voltage regulator, engine governor and control system to work together. Therefore, generator performance data is critical when sizing generators for motor starting. Performance testing of generators is critical to determine the true capability of a generator system.

In the absence of generator performance data, and expensive sizing software the alternative tool a technician has at their disposal to estimate the size of the generator needed to estimate the voltage dip is the NEMA MG-1 equation. Caution should be exercised when applying this equation because it can be overly aggressive, and it assumes constant frequency and is solely based on the reactance of the alternator.

Using this equation can only estimate what the alternator can do, and it ignores the impact of the excitation / automatic voltage regulation system, the impact of kW load applied to the engine, the effects of engine speed change have on frequency and voltage recovery.

Special consideration must also be given to the characteristics of different types of motor starting methods because they can have a direct impact on generator sizing requirements and other connected loads.

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Please note: As always generator installation should be done in accordance with local, state and national electrical codes and by a qualified licensed professional.

For additional support please contact Multiquip Technical Support & Training.

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Additional papers written by author: Grounding & Bonding; Temporary Power Generation and Electrical Distribution, http://service.multiquip.com/files/2-20190326-073209.pdf

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