Application Guidance Notes: Technical Information from Cummins Generator Technologies

AGN 017 - Unbalanced Loads

There will inevitably be some applications where a Generating Set is supplying power to multiple and various loads that subject the alternator to an unbalanced load situation.

UNEQUAL PHASE LOADING

Alternators can be subjected to unequal phase loading, but this will result in unequal phase voltages. Employing a three phase sensing AVR will always ensure the best possible overall voltage regulation and will always be nominated if an alternator is to be used to supply power to multiple loads where an unbalanced load condition may arise. For further information and graphical detail of the performance of 2 phase and 3 phase sensing AVR's, contact applications@cummins.com.

The effects of an unbalanced load situation on an alternator can be complicated and is explained in the following two sections. Section 1 tries to keep it simple and uses a mix of mechanical and electrical analogies to help convey the technical information. Section 2 attempts to provide a more in depth technical appreciation of what is happening inside the alternator.

SECTION 1

Single phase loads subject an alternator to an uneven/pulsating electrical load and so, uneven demand for torque over the 360º of rotor and crankshaft rotation.

Think in terms of a multi-cylinder engine, but for conditions where reduced power is required and the 'fuel' system to this engine is able to feed less than all cylinders. The result would be an engine that would be capable of supplying the required reduced power yet still able to maintain speed. However, the rotational speed of the crankshaft would be 'jerky', resulting in an engine that would run with high levels of torsional-vibration, whilst subjecting the mechanical assembly of engine and alternator to high levels of physical vibration.

Now imagine a three phase alternator [or three cylinder engine], connected to a load on only one phase [feed fuel to only one cylinder]. The alternator's phase current and so load would be within this single phase's capability by being within one third of the alternator's three phase designed rating [or for the engine within the capability of just one of the 3 cylinders]. The end result would be a rough running Generating Set.

In the world of rotating electrical machines, i.e. alternators, the effect of any load current can be described in terms a "phase sequence condition" [not to be confused with UVW phase rotation]. Basically, a balanced three phase load is said to have a Positive Phase Sequence condition, unbalanced loads across the three phases is described by the term Negative Phase Sequence Condition and a short between all three phases would be described as a Zero Phase Sequence condition.

When a three phase Generating Set is supplying a balanced three-phase load, the torque demand from the engine is very balanced and virtually linear over the 360º of each revolution. Under an unbalanced load condition, the worst case being no current in two phases and full rated current in just one phase - therefore a single-phase load - the demand for engine torque over the 360º of each revolution is very unbalanced.

Simplified, it can be considered that for a total of two thirds of the revolution no power is being demanded. This results in the rotor circumferential speed varying over the 360º of each revolution. In turn, this results in the rotor's damper cage becoming very active, trying to damp-out circumferential speed variations and under extreme levels of negative phase sequence conditions, the aluminium damper cage will become 'so active' that it actually melts.

Refer to **AGN016 Negative Phase Sequence Currents** for more information.

AGN016 explains the load balance restrictions that are in place for negative phase sequence conditions, to comply with the performance standards in IEC 60034-1. Actual alternator capability extends beyond the requirements of IEC60034-1, to provide the following compensation that must be invoked to maintain alternator serviceability:

1. If the alternator is to be applied to a load that is connected to just one of the three phases and Neutral, then the load current must not exceed 25% of the rated output current [I_L].

   Note: the kVA calculation is simply; phase-to-Neutral voltage (L-N) x current.

2. If the alternator is to be applied to a load that is connected across just two of the three phases, then the load current must not exceed 30% of the rated output current [I_L].

   Note: the kVA calculation is simply; phase-to-phase voltage (L-L) x current.

Single Phase Loads.

By connecting a three phase winding into a Double Delta connection [sometimes parallel Zig Zag] all three phases will handle a portion of the single phase load and the negative phase sequence condition – or to use the technical term: the negative phase sequence current I_2 - will be reduced.

Some alternator designs are such that it is not possible to reconnect the three phase winding for single phase loads. If the alternator is required to operate with some three phase load, but a high level of single phase loading on just one phase, then very careful considerations need to be taken to ensure that the resulting Negative Phase Sequence Current [I_2] situation will not damage the alternator.

Cummins Generator Technologies manufacture alternators that are designed specifically for single phase operation. The dedicated single phase stator winding numbers are 05 and 06. These windings are rated after very careful consideration of the capability of the rotor damper cage.

It is possible to reconnect 12-wire, three phase stator windings for single phase loads. When this is done, the output power must be reduced. The single-phase ratings can be seen in the single phase datasheets for each alternator or by contacting applications@cummins.com.

SECTION 2

The following is offered as a more technical explanation of the effects of unbalanced loads on an alternator and resulting component stress. It has been written in the form of answers to the most commonly asked questions about unbalanced loads and their effects on alternators.

Question: What calculation is required to identify the level of Negative Phase Sequence Current [I_2]?

Answer: We could say this calculation is best understood by reading electrical machine design textbooks. The calculations are based on phase angle relationship of all alternator components and assemblies involved and then extensive mathematical use of 'J' operator / 'J' notation based calculations to identify resultants and their effects. For reasoned guidance on calculation methods without detailed too much consideration of the complexities, refer to AGN016 Negative Phase Sequence Current.

Question: Explain in more detail the way that I_2 currents are actually generated in the rotor?

Answer: When an alternator is under load there is an internal load-angle of the rotor's physical and actual mechanical position with relation to the effective position of the magnetic flux emanating from rotor pole-face, compared with the resulting generated voltage waveform status/level in the stator winding.

Under steady state balanced three phase loads at full load, this angle is (virtually) constant and rotor is typically 35 electrical degrees mechanically/physically advanced of that instant-in-time generated voltage waveform. In other words, the engine crankshaft and the coupled rotor are some 17.5 mechanical degrees in front of the generated voltage waveform.

For simplicity, assume it's a proportional relationship, zero load + zero degrees of load angle; half load = half the 35 electrical degrees, etc. The actual mechanical degrees are half the electrical degrees because it's a four pole design of generator. Under this steady state condition, the rotor airgap flux is rotating in-phase with rotor and condition described as 'positive phase sequence' condition [I_1] with no 'slip'.

Reduce, or increase, the actual balanced load and there will be a change to the alternator's internal operating load angle and this results in a momentary 'rotor-slip' within the established magnetic flux field, relative to the original load's level of steady state operating conditions and load angle. Because of rotor 'slip' occurring - as the new load angle is established - a voltage is induced into the damper cage and so, current flows through the rotor damper cage. The net result of the damper cage current is a complex flux caused by current in the damper's pole face bars, working against the load currents armature reaction and the original air gap flux generating the output voltage and all 'mixing' in the rotor/stator air gap. The flux resulting from the damper cage activity acts to generate a 'mechanical damping' torque and this 'damps out' the rotary +/- oscillations of the rotor as it settles into its new load angle displacement position.

Now imagine that the alternator is not supplying a balanced three-phase load, but instead different load currents flowing in each phase. The required operating rotor load angle will be different for each of the different phase currents [loads]. But at least all three phases are loaded, so the rotor has a continuous, but different, load angle for each of the three-unbalanced phase loads.

Now go to the extreme condition of only one phase being loaded and the rotor load-angle is effectively zero electrical degrees when in alignment for the two unloaded phases and then 'pushed' to the required load angle when aligned with the loaded phase. So for a four pole machine, at 1500rpm for 50Hz output, thereby generating two voltage cycles every revolution, the rotor load angle will change considerably eight times every revolution.

This is why a Generating Set supplying a single phase load has vibration levels some 20% to 30% higher than a generator supplying a balanced three phase load. It is also why an engine delivering a given level of kWm for a balanced three phase load will run with lower exhaust gas temperatures, and better fuel economy, than when delivering the exact same kWm in to the pulsating power demand of a single phase load.

But if the three phase windings are connected into a connection such as Double Delta, then at least all three phases are carrying current and so contributing towards the single-phase output required. However, the current through the phases that form the greater part of the delta circuit have load originating current 'pulled' through them out-of-phase with the voltage that is being generated in them. This leads to more complex considerations of what's happening within the stator and rotor components of the generator and more J notation calculations are required to calculate the resultant effect on individual component rating and capability.

Question: How are currents induced into the rotor damper cage?

Answer: Voltage is induced into any conductor if it moves at right angles through a magnetic field. For a given conductor, the faster it cuts through the magnetic flux the higher the level of generated voltage. When the rotor is running under steady state balanced load conditions, the magnetic field of the rotor flux is moving at exactly the same speed as the rotor and so, in relative terms, zero flux cutting speed with regard to the damper cage. The moment the rotor slows down or speeds up, because of a load increase or decrease, then the original operating load-angle must change and that means that the damper cage is suddenly moving through the fundamental magnetic field / flux in the air gap between stator and rotor. This relative movement through the flux generates a voltage in the damper cage, just as the designer intended and the as the ends of the bars are welded together current flows through the damper cage assembly, to generate flux, which in turn provides a damping torque within the 'damper cage' to help with 'controlled and damped' mechanical re-alignment of the rotor to the now required load angle position.

Question: Why can't the AVR reduce the rotating magnetic field for the part of the rotor cycle when it is aligned with the two unloaded phases?

Answer: Although the electronics within the AVR have a time constant of micro-seconds, the magnetic field of an alternator works on much longer/slower time constants. Typically, the time constant of the exciter - which is supplied by the AVR - is some 80ms, whilst the main rotor which 'driven' by the exciter output takes some 250ms to make a real change to operating flux levels. So the alternator's complete excitation system is far too slow to make the necessary changes in the required times to help with a negative phase sequence condition, which are occurring four times every ac voltage cycle [20ms] and not in four even time spacing's.

Question: Some alternator manufacturers suggest taking the 240V single phase from across just two phases. Is this correct?

Answer: Using just two phases of a three-phase alternator must be a compromise situation. It may be based on the alternator being designed to operate at 480V three phase [277V, L-N] in series star and then capable of offering 240V across two phases once the alternator has been connected into parallel star, because half 480V = 240V. This method of loading two of the three phases has to be an improvement over loading just one phase of the three phase winding in order to provide a single phase output.
But the Double Delta configuration does load all three phases and has been proven by all alternator manufacturers to be the best compromise way of getting back to near balanced conditions inside a three phase alternator when a single phase load is connected. In the Double Delta connection, the phase windings in the greater part of the delta circuit handle about 40% of the total load current, with the 'master' phase in I part of the delta handling some 60% of the total single-phase output current.

Question: What about alternators fitted with a dedicated single-phase winding?

Answer: A stator fitted with a dedicated single-phase winding has one third of its stator winding slots empty. This means that there is a lot more space for cooling air to travel through the centre of the alternator in the space between rotor and stator. This increased cooling air will flow over the rotor pole faces and will reduce the working temperature of the rotor pole face and so in turn the damper cage. This extra cooling is taken into account when the single-phase alternator is being designed and the alternator's output ratings are being identified.

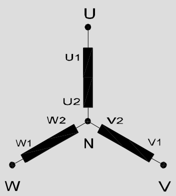
CONNECTION DIAGRAMS

Winding configurations and winding numbers.

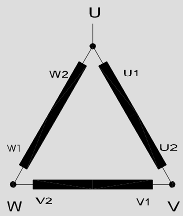
6-Wire Connections.

Stator Winding numbers 12/312, 13, 07 and 26 are the most common windings with 6 stator exit leads that are brought into the terminal box. The 6 leads are normally connected in a Star configuration, although it may be possible to connect the leads in a Delta configuration if the requirement is stated at the time of order. It is not possible the re-connect from Star to Delta or from Delta to Star.

Star 3Ph 4W
Output Terminals (U.V.W.N.)

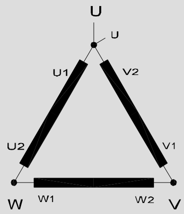


Delta 3Ph 4W
Output Terminals (U.V.W.)



BC, UC, & HC4

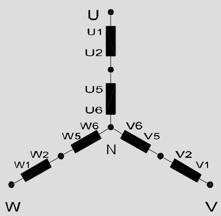
Delta 3Ph 4W
Output Terminals (U.V.W.)



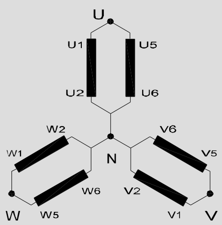
12 Wire Re-connectable.

Stator Winding numbers 11/311, 14, 17 and 25 are the most common windings with 12 stator exit leads that are brought into the terminal box. The 12 leads are normally connected in a Series Star configuration, but may be connected Series Delta or Parallel Star, depending on the required output supply voltage. It is possible the re-connect to configured for Series Star, Series Delta or Parallel Star.

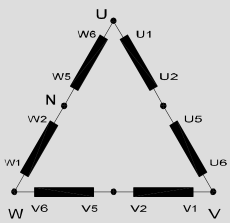
Series Star 3Ph 4W
Output Terminals (U.V.W.N.)



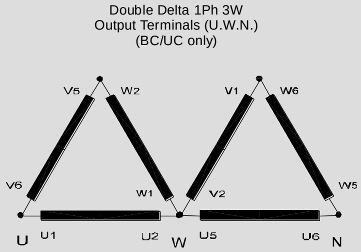
Parallel Star 3PH 4W
Output Terminals (U.V.W.N.)



Series Delta 3Ph 4W
Output Terminals (U.V.W.N.)

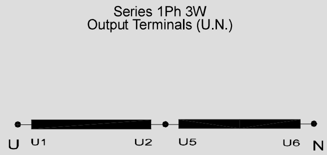


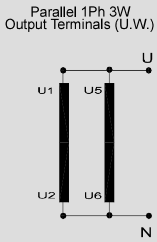
It is also possible to connect 12 wire Stator Windings for single phase operation in the Double Delta configuration.



4 Wire Dedicated.

Stator Winding numbers 05 and 06 are specifically designed for single phase operation, and cannot be re-connected for three phase supply. Winding 05 is dedicated to voltages at 50Hz and Winding 06 is dedicated to voltages at 60Hz.





REFERENCES

An investigation into the various applicable Standards has resulted in the following observations:

ISO 8528 Part 3. Section 8.11 Identifies Voltage Unbalance $\delta U_{2.0}$ (Ratio of the negative sequence or the zero sequence voltage components to the positive sequence voltage component at no-load. Voltage unbalance is expressed as a percentage of the rated voltage). Table 1 then identifies the expectations for 'Operating limit values' for Performance class: G1, G2, G3, and G4, each of these requires $\delta U_{2.0}$ (see above) to be within 1% under no load conditions.

ISO 8528 Part 3. Section 10.1 Unbalanced Load Current. The alternator shall be capable of operating continuously with a Negative Phase Sequence Current up to and including 10% of rated current.

IEC 60034-1. 7.2 Form and symmetry of voltages and currents.

7.2.2 AC Generators. Three-phase AC generators shall be suitable for supplying circuits - which are virtually non-deforming and virtually balanced - that is to say - the generators sinusoidal output voltage when applied to such a load may result in unbalanced phase currents of < +/- 5%, and the resulting Negative-sequence component or the Zero-sequence component must not exceed 5%.

7.2.3 Table 2 – Unbalanced operating conditions for synchronous machines. This table states that Indirect cooled generators, eg: standard open ventilated - IC01 Shall be capable of continuous operation with an unbalanced load where the Negative-sequence component I_2 / I rated, should not exceed 8%.

NEMA MG1 Part 20. Large Machines – Induction Machines. 20.24 effects of unbalanced voltages on the performance of polyphase squirrel-cage induction motors. This identifies the associated problems, and shows a graph with exactly the same de-rating factor as that in 00/203105. In summary: with an applied voltage unbalance of more than 1% a de-rating factor must be introduced, and the graph indicates a de-rate factor out to 5% phase voltage unbalance, where derating factor is 0.75

NEMA MG1 part 32. Synchronous Generators. 32.14 Continuous current unbalance. Permissible I_2 for a generator with interconnected amortisseur winding = 10%

CONCLUSION

Although in Table 1 of ISO 8528-3 guidance is found regarding the No-load phase voltage unbalance – which should be within 1% - no standard could be found that stipulated a maximum allowable level of phase to phase voltage unbalance in percentage terms for practical guidance for an On-Load condition.

For the reasons outlined in IEC 60034 – 1 it is the characteristics of the connected unbalanced load which force the phase voltages to become unbalanced, but the engineering standard falls short of quantifying a maximum allowable unbalance in practical V % terms.

Instead guidance is offered in the form of maximum advised level of unbalanced phase currents, and this is identified as the percentage of negative sequence I_2 and zero sequence I_0 components with regard to the alternator's rated current I_N.

This makes very good sense, because the effect of any unbalanced phase voltages would be to promote unbalanced phase currents. And it is the level of unbalanced phase currents that cause alternator [and motor] components to become thermally stressed, and their design be subjected to operating with unbalanced; continuously pulsating conditions.

When considering the percentage levels of I_2 that are stipulated there are differences, but alternators are designed with capability levels above the 8% in IEC 60034 and the 10% in NEMA and ISO 8528-3, with this slight disparity being considered acceptable.

Any layman using the standards as a reference document for a field in which they have limited experience the use of negative and zero sequence components is unlikely to be immediately helpful, although benefiting from exposure to technically correct terms.

A really helpful standard would have a table of the actual levels of phase current un balance, and an associated derating factor similar to the NEMA graph in Part 20.