APC APPLICATION NOTE #166

Application of Generators for MGE Galaxy UPS Systems

By John Boyle

Introduction

For long term outages MGE Galaxy UPS systems require an alternative back-up source of supply when the primary supply fails. Depending on application, for the majority of cases diesel alternators (or more often referred to simply as generators) are used as back-up.

Electrochemical energy storage in the form of dry lead acid cells is the main source for bridging changeovers (C/O's) to the back-up supply. For MGE Galaxy UPS systems > 500kVA, five to fifteen minutes is typically specified as both economic limit and sufficient autonomy time for safe shutdown in the event of start-up failure of the back-up supply.

Energy taken out of batteries when bridging the C/O must of course be replenished by the back-up generator which must also provide for inrush surges of critical UPS loading and building services plant such as chillers and downstream transformers. The latter may be subject to load shedding and timed start-up sequencing to minimize surge loading on site generators. The generator(s) must be able to maintain stability during this period and during any subsequent faults in the distribution network and be rated according to the needs of the overall load and specification of the project.
The purpose of this application note is to provide guidance on these matters.

Diesel alternators

For the purposes of this Application Note a diesel alternator consists of a turbo-charged diesel engine (prime mover) coupled to a salient (i.e. protruding) 4-pole rotor. The rotor rotates at a synchronous speed of 1500rpm (50Hz applications) or 1800rpm (60Hz) inside a permanent magnet stator which has a three-phase, 4-wire wye connected LV winding. Forced air cooling of engine coolant water is provided by a fan coupled to the shaft. Engine speed control by regulating fuel supply is performed by an electronic speed governor in response to load demand. Current demand (for a given line voltage) is controlled by varying rotor/stator excitation via a separately excited automatic voltage regulator (AVR). The important point to note is that the engine determines mechanical power (kWm) whilst the alternator determines amps. For a detailed explanation of generator operation refer to White Paper 93.

Generators vary enormously depending on application. For a simple system such as a 100kW critical load supported by a unitary or N+1 MGE Galaxy UPS only, the generator may be a 6-cylinder 6.7 litre automotive based engine and self-excited alternator housed within a container with an integral base mounted plastic fuel tank. At the other extreme the load maybe several MVA (including building or essential services) and comprise several sets in parallel. If for example each set is 2.5MVA rated the engine could be a V-16 cylinder, 60 litre cubic capacity with all sets housed within a dedicated plant room. Such a system will require synchronizing panels together with extensive monitoring and relay protection panels whilst engine fuel supply may be contained within an external 150,000 litre bunded steel bulk storage fuel tank with double skinned fuel pipes and leak detection. Bunding refers to a means of secondary containment such as a lined catch pit in the event of tank spillage.

Rating

Universal standard ISO8528 is used worldwide for specifying generator sets. The standard is in 12 parts of which part 1 defines ratings for continuous operating power (COP), prime power (PRP) and emergency standby power (ESP). For MGE Galaxy UPS applications the number of hours per year @ 100% ESP should not exceed 25 hours or 200 hours @ 80% of ESP. Minimum load should always exceed 30% of ESP below which engine damage may occur over the long term. ESP rating represents maximum limit on the generator, there is no overload capability beyond this rating.

PRP is restricted to an aggregate of 500 hours per annum @ 100% of PRP and at an average of 70% for any continuous period of 250 hours. PRP rating is 10% below ESP rating and COP is typically 20% margin below PRP for unlimited hours. A COP application could be for example a site with no mains utility with sets run continuously at base load to support the entire infrastructure. To extend useful life continuously operating gensets may be 8-pole, 750rpm with larger bore, 6-cylinder in line configuration compared to much smaller, lighter, lower cost and higher speed standby sets.

Generators are always specified with ESP (kVA) @ 0.8 lagging power-factor (or 36.9° displacement), hence active power P(kW) = ESP x cos36.9° = 0.8 x ESP, reactive power Q(kVAR) = ESP x sin36.9° = 0.6 x ESP. For example a set rated at ESP = 2250kVA can be defined in ESP = P + jQ format as 2250(kVA) = 1800(kW) + j1350(kVAR), PRP = 2000kVA or 1600(kW) + j1200(kVAR). Exact ratings depend on manufacturers' range of sets and can apply up to 40°C ambient and 1000m above sea-level. However ISO8528 states 27°C and 150m respectively and 60% Relative Humidity. Check with manufacturer as to limits beyond which derating is necessary; note that RH levels only affect naturally aspirated engines. With good maintenance, a generator run at 70% of PRP may well give 30,000 hours operating life, whereas for standby operation it may see < 500 hours service after 10 years.

Efficiency

Only about 35% of fuel energy (BTU's or kJ's in) is converted into mechanical energy. Electrical power out kWe = kWm x ηa where alternator efficiency $\eta a \approx 96\%$ (typical full-load efficiency of a 1000kVA alternator). ηa diminishes with loading and with smaller sets (mainly due to proportionally higher I2R losses of winding). For example (allowing for fan losses) a 1000kVA/800kWe set requires an engine rated >850kWm.

The process of converting internal combustion of a reciprocating engine into rotational mechanical energy is highly inefficient and generates surplus heat energy which has to be dissipated into the environment (unless utilized in Combined Heat & Power applications which is not within the scope of this document). The exhaust system extracts about 30% of heat energy; forced air cooling of the radiator extracts a further 25% with about 7.5% directly radiated from the engine block. The remainders are alternator losses (including radiated losses from the casing) and coolant fan losses. Hence overall efficiency is ≈ 33 to 35% depending on engine size.

On account of cooling requirements by way of example a 2.5MVA, 2MW generator with a 60 litre, V-16 engine requires about 50m3/s air-flow of which 10m3/s is required for the cooling jacket, 36m3/s as drag across the engine frame and about $3m^3/s$ for internal combustion purposes. Air flow should ideally be in line with the axis of the generator in the direction of alternator toward the fan. Total inlet air aperture area should exceed cooling jacket cross-sectional area by >1.5x.

Operating Diagrams

Generators are unable to absorb reactive power (kVAR) to the same degree as the mains supply or even a UPS of the same rating. The voltage of an inductive reactive source (i.e. synchronous reactance Xd under steady state synchronous speed and sub-transient reactance X″d under dynamic conditions) will increase if it imports kVAr's. As output volts increase the alternator AVR attempts to reduce excitation until it eventually loses control causing instability. Increasing generator voltage may damage the load unless protective means are incorporated to shutdown the machine. Similarly regenerative loads such as lifts can export real power back into the generator which if not dissipated elsewhere can cause the engine to over speed and shutdown.

The operating curve specific to a 1400kVA generator is shown in **Figure 1** (courtesy of Newage International), sometimes referred to as a P-Q diagram. It shows the machines ability (in per unit or pu terms) to generate and absorb active power P and reactive power Q as a function of load power factor. Although the alternator may be rated higher in kW terms, active power is limited according to engine size. The generator must be operated within the boundaries of the operating curve. By extrapolating radially for a given power-factor, max P(pu) can be read off horizontally from the intersection with the operating boundary and max Q(pu) read off vertically. P(pu) and Q(pu) are then scaled according to the alternator ESP rating.

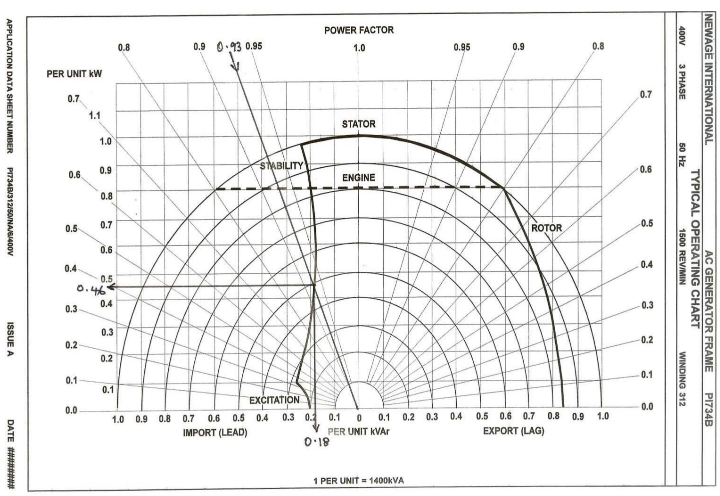

Figure 1. Example of operating curve for a 1400kVA generator

Of particular interest to UPS systems is generator performance on leading power-factor loads when confronted by contemporary data centre loading. The emphasis has now shifted away from highly distorted waveforms of the past to leading displacement loads due to legislation imposed upon IT equipment such as EN61000-3-2. As can be seen from the operating chart in **Figure 1** only about 20% of ESP rated kVAr's can be imported for a leading power-factor of 0.97. Data centre power-factors tend to be worse than 0.97, to overcome this problem either a bigger machine needs to be specified, an existing one de-rated or a means provided of improving load power-factor.

Sizing in relation to UPS

If a generator is backing up critical IT services, sizing of generator must consider:

i. UPS loading and efficiency at that loading including battery recharge
ii. UPS 'front-end' characteristics, i.e. input power-factor, balanced/unbalanced input current, total harmonic current distortion (THID) and its effect on generator total harmonic voltage distortion (THVD)
iii. Characteristics of load in the event of transfer to maintenance bypass during generator operation
iv. Cold start load acceptance and inrush surge at generator handover and its effect on generator speed-droop and alternator transient response
v. Effect of any building services surge loading

Regarding item (i) many MGE Galaxy UPS products unlike their predecessors are actively power-factor corrected with a programmable soft-start period over several seconds. This makes the genset selection process easier in the sense that (ii) power-factor, unbalanced loading and THID are not factors unless (iii) above is considered.

Worked Example 1: A 400V, 160kVA, 144kW rated UPS with unity input power-factor supplies max rated resistive loading. Battery charging is rated @ 10% active power rating and working efficiency is 0.94pu under these conditions. The generator will see (144 +14)kW/0.94 = 168kW. To rate generator requirement at this figure is bad practice as no margin is provided beyond standby rating of generator and 'turbo-lag' load acceptance as per (iv) above. On account of these factors it is prudent to limit max load on generator to 75% of ESP. Hence above case requires a generator to be rated at ESP >275kVA, 220kW.

Worked Example 2: Now consider 3 x 400kVA/kW rated MGE Galaxy UPS's operating in an N+1 parallel redundant mode. Each unit has same input characteristics and battery charging rating as previous example but data centre load requires 750kVA @ 0.93 leading power-factor (rule of thumb do not exceed 80% - 90% active rating of UPS in N-state). UPS efficiency given as 95% assuming balanced loading. The site requires that during corrective maintenance the generator must supply the UPS suite, hence (iii) above applies.

To specify the generator as before requires P = ((750kVA x 0.93) + (3 x 40kW))/0.95 = 860kW, Q = (750kVA x (1 – 0.932)1/2) = 276kVAr, hence stipulate 1400kVA, 1120kW as nearest preferred generator. However from generator operating (P-Q) diagram, see **Figure 1**, a data centre load of leading power-factor 0.93 in maintenance bypass operation would yield P = 0.46pu x (1400 x 0.8) = 515kW and Q = 0.18pu x (1400 x 0.6) = 151kVAr resulting in a de-rated generator of S = (5152 + 1512)1/2 = 537kVA. Clearly a larger machine is required. Note that P-Q envelope varies according to frame size and between manufacturers. A selected 1800kVA frame size yields P = 0.75pu = 1080kW, Q = 0.3pu = 324kVAr, S = 1128kVA under these conditions and min operating load > 0.3 x 1800 x 0.8 > 432kW is satisfied. Alternatively an active PF conditioner could be used to absorb some of the kVAR enabling a smaller frame size to be specified.

Many of the larger MGE Galaxy rated UPS systems use 6-pulse and 12-pulse phase controlled thyristor rectifiers (with added harmonic trap filters) and phase-shifting transformers to reduce input THID. More severe regulatory requirements (such as G5/4 in the UK) impose limits on total harmonic voltage distortion (e.g. THVD ≤ 5%) when the distortion current interacts with the utility source impedance (as defined by a short-circuit fault level supplying the building infrastructure). If these levels are exceeded the REC (Regional Electricity Company) can insist upon mitigation under the threat of disconnection.

The THVD level does not apply when the infrastructure is supported by standby generators (unless they are connected in parallel to the utility supply) so a figure of THVD = 10% is generally applied so as not to cause malfunctioning of essential services connected to the same busbar as the UPS. If the generator is loaded only by the MGE Galaxy UPS then THVD can be increased further depending on specification of UPS system. Subtransient reactance X″d which is proportionally much greater than utility reactance is required for this purpose. Therefore for a given THID, THVD will be much greater when on generator back-up and this makes generator selection more involved than previously.

Worked Example 3: Consider a 625kVA, 500kW rated MGE Galaxy UPS with a 6-pulse thyristor controlled front end complete with 5th harmonic trap filter. At 500kW loading when combined with 15% max battery recharge it has a working efficiency of 92%, an input power-factor of 0.9 at nominal 415V. It is required to maintain a THVD figure of ≤ 10% and an undervoltage dip of <15% during generator hand-over.

Apparent power demand S = (500kW + 75kW for battery recharge))/(0.9 x 0.92) = 694kVA and P = 0.9 x 694 = 625kW. Assuming generator to be operated at 75% of ESP, select a 1040kVA, 832kW rating. Machine X″d is expressed in per unit terms for base quantities of kVA and volts, from machine data X″d given as 16% @ 1040kVA, 400V.

Adjusting for dynamic conditions X″d = (694/1040) x (400/415)2 x 16 = 9.9% which from **Figure 2** complies with THVD limit of 10%. If the battery charger is inhibited during handover (assuming efficiency and input power-factor are unaffected, then 75kW/0.92 = 82kW net reduction in demand occurs, ie 604kVA, 543kW) resulting in X″d = (604/1040) x (400/415)2 x 16 = 8.6%. Selecting a machine with a lower X″d will result in further THVD reduction.

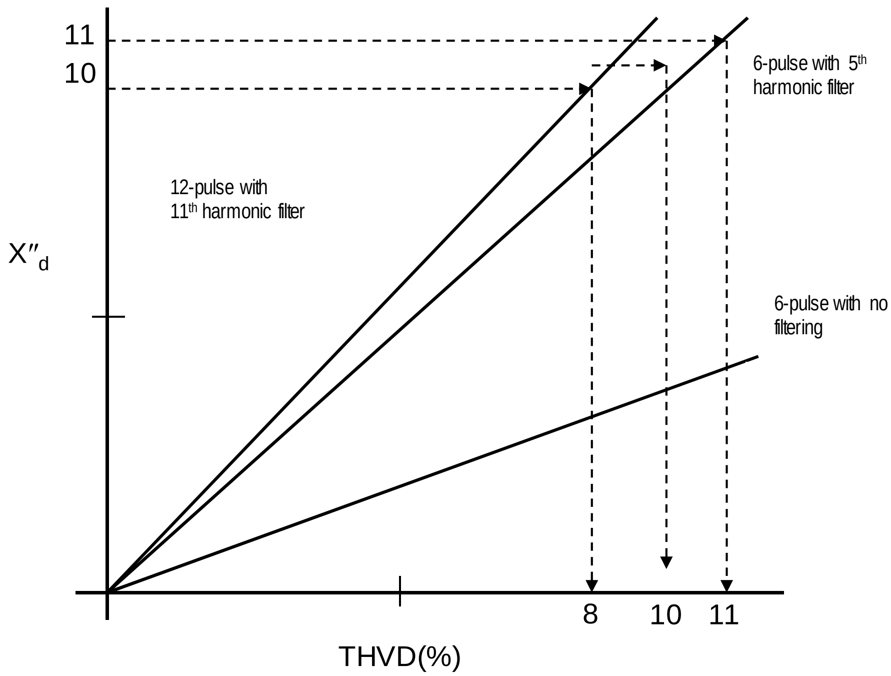

Figure 2. shows calculation of THVD when adjusting for dynamic conditions

However during battery operation the front-end of the UPS looks like a 'detuned' 5th harmonic LC filter since the thyristor bridge is turned off. When the generator engages with the UPS it will see about 30% kVAR import from the LC filter until the rectifier ramps up to a point where the rectified DC exceeds battery voltage. 30% of 604kVA ~ 180kVAr import exceeds a 1040kVA generator capability. Therefore a 1600kVA generator maybe required (with UPS battery charger inhibited) unless a compensated LC filter is used.

In the majority of applications generators support an equivalent amount of essential building services load (e.g. chillers, HVAC, lighting, etc) in addition to the UPS backed critical services load. Much of the essential services loading will be induction motors which present about 0.85 lagging power-factor and so can be used in canceling out leading kVAr's if the UPS system is forced to bypass. Considering (v) above in reality the generator(s) will see an inductive load with high inrush surges which need to be time staggered until steady base load conditions prevail.

Regarding voltage dip, generator transient performance is defined by ISO8528 part 5. Generators are specified from G1 to G4 where the latter represents highest performance in terms of voltage deviation and speed droop (frequency reduction) or V/Hz in response to % step loading. Isochronous speed governing refers to constant engine speed, regardless of load (within the rating) of the engine. In reality G3 and even G2 are acceptable as MGE Galaxy UPS products are highly tolerant to incoming voltage variations, distortion and frequency deviations (as defined by EN50160). Generator load acceptance charts show % voltage dip, % frequency dip with voltage and frequency recovery times in seconds for % step-loads of 25, 50, 75 and 100%. The end-user should ensure if large load transitions are applied in practice that alternator voltage dip is <15% recovering in typically <2.5 seconds followed by lesser loading with corresponding reduction in voltage dip and recovery time. Transient response is dependent on many factors beyond the scope of this document e.g. engine break mean effective pressure (bmep), AVR characteristics, engine size, whether engine is hot or cold, naturally aspirated or turbo-charged, load power-factor, and so on.

Another important factor is the rate of change of frequency (abbr. ROCOF) during transient response time vs. load acceptance. UPS terminology refers to this as frequency slew-rate, or df/dt. If the UPS slew-rate is set too low then during load sequencing on generator back-up a high ROCOF may force the UPS to decouple if it loses phase-lock with the generator. The UPS will attempt to resynchronize after transferring to battery operation, to prevent this happening increase df/dt ≥ 4Hzs–1.

Environmental Issues: Fuel Requirements, Exhaust Emissions, Acoustics

Turbo-charged diesel engines consume about 0.28 litres per kWh based on PRP rating using grade A2 red diesel fuel. Hence a 1400kVA (1120kW) standby set operating at PRP loading consumes about 70 litres over a 15 minute autonomy time. To have 24 hour back-up requires 6,770 litres. A day tank and external cylindrical 9,000 litre bulk storage fuel tank (approx. 1.98m diameter and 3.2m length) would suffice under these circumstances. Local fire regulations apply regarding installation of bulk fuel tanks and the way in which fuel is pumped up to the engine. Diesel fuel needs to be replaced every year as it absorbs moisture and deteriorates over time. Red diesel has a density of 0.85kg/litre and retails at about £0.5 per litre in the UK.

Exhaust from internal combustion engines produces about 99.9% gas (including CO2) and 0.1% aggregate of ‘acids’ and particle matter such as carbon. It is the latter which is subject to control by catalytic converters, urea traps, gas recirculation and particulate filters. In Europe there are no emission standards for emergency standby sets or for engines >560kWm when operated continuously. However European Union NRMM standard (stage II) applies to engines <560kWm and will be harmonized with the North American EPA standard (tier 3) within the next few years.
In standby operation the engines throttle up very quickly producing copious amounts of black smoke due to excess unburnt fuel. After a few seconds the engine stabilizes and the emissions appear ‘grey’. Some manufacturers provide ‘soft-starting’ to overcome black smoke emissions especially useful in applications where office blocks/residential areas might be in close vicinity.

Sound pressure level (SPL) is measured in Pascals and varies with distance from the source. By applying a weighting factor akin to human hearing characteristics it is given an ‘A’ weighting in units of dBA. EU legislation is covered by 2000/14/CE directive. For sets rated at PRP ≤ 400kW stage II states that dBA = 95 + log10PRP. Therefore a 320kW engine must not exceed 97.5dBA. An engine without an exhaust silencer would typically emit noise at 120dBA, fitting a silencer could reduce this by 30dBA. A 3dBA reduction corresponds to a halving of noise level. To get some idea of 30dBA reduction (call it r) then 30dBA = 10log10r so r = log–1 (30/10) = 1000! Adding exhaust silencer noise to engine noise (say 86dBA) results in an overall noise level of 10log (log–19 + log–18.6) = 91.5dBA.

Generators installed near residential property are subject to much more severe noise specification (40 to 50dBA). The acoustic enclosure would need to be lagged with suitable noise absorption material, air baffles fitted on air inlet/outlet louvers and larger exhaust mufflers on the exhaust pipework. Fully integrated gensets installed within purpose built enclosures to EU legislation are typically 80dBA @ 1 meter reducing by 8-10dBA for every 6m further from the enclosure. A detailed description of noise measurements is beyond the scope of this document. Containerized gensets find wide usage in data centers installed externally to the IT Pod's. To save on footprint large sets mounted in 20 or 40 foot ISO containers can be stacked vertically and deployed elsewhere should the need arise.

Fault Currents, Protection Co-ordination, MV/LV gensets

Self excited alternators are incapable of supporting three-phase faults since a shorted output will remove the AVR's power supply and stop the machine. However it can support a phase-fault as the other two phases will supply the AVR. Separately excited machines by definition have a separate source of power derived from a permanent magnet generator (PMG) driven by the rotor shaft. If the machine is subject to a three-phase fault the AVR supply is isolated from the alternator output.

Generator fault currents are calculated using the machines specified reactances, i.e. subtransient X″d, negative sequence X2 and zero sequence X0 (strictly speaking these are impedances but in the case of gensets X >> R). For a detailed explanation of these terms refer to IEC60909-0.

Machine reactances are normally quoted either in % or pu terms. Ohmic values can be obtained from X = X(pu) x VL2/S where VL is line voltage. If X″d = 0.16pu then a three-phase fault current I″K3 = Io/0.16 (where Io is max load current in standby operation) sustained for a subtransient time constant T″d of typically 20 to 30ms. Because X/R ratio of the fault is high, fault currents have high asymmetry which may cause large withstand forces on cable bracing and switchgear. If the fault isn't cleared, machine reactance increases gradually to its saturated synchronous reactance XS (typ 0.33pu). Hence short-circuit current is approximately 3 x Io sustained until protective relays shut the machine down within about 10 seconds.

A phase to earth fault current I″K1 can exceed symmetrical faults as loss of voltage on the faulted phase is overcompensated on the other phases by the AVR. Using Ohmic values of machine reactances I″K1 = 3 x VP/(X″d + X2 + X0) where VP is phase voltage. The fault currents are based at the machine terminals (near-to). Cable impedances must be added if the fault is far-from, in practice cable and arc impedances significantly reduce theoretical values. In addition any regenerative loads (ie induction motors) if connected to the same faulted busbar will backfeed into the fault and augment I″K3.

LV generators in comparison to MV/LV distribution transformers (of the same rating) have significantly less fault current capability. A distribution transformer has less pu reactance and practically an infinite bus behind it. Protection overlays, co-ordination and selectivity exercises must allow for this. Ideally the generator must be able to discriminate with the highest rated UPS incoming and outgoing feeder breakers on time-current overload. Symmetrical, phase to phase and phase to earth faults will transfer the UPS to electronic bypass switch (EBS) which requires co-ordination on I2t with generator time constants. The alternators safe operating time-current limitation is best protected by MCCB/ACB's with electronic trip units and I2t capability rather than thermal-magnetic devices. Consult manufacturers regarding their recommended protection and control schemes. Unbalanced loading on a 4-wire wye winding will result in negative and zero sequence currents which also cause extra heating within an alternator and should be avoided, again consult manufacturers as to safe limits. The onus is on site Facilities Management to balance loading.

Mechanical and electrical relay protection of the generator is dependent on the size, application, and number of units in parallel and is beyond the scope of this document. The single line diagram of **Figure 3** shows LV generators installed in a tier 3 data centre. It shows five active UPS systems with an idling reserve to back-up critical services of any one failure of an active MGE Galaxy UPS. This methodology reduces capital expenditure of dual redundant systems and data centre PUE. The cast resin distribution transformer is packaged within the LV switchboard as a sub-station with a dedicated nearby centralized generator plant room and fuel tank with day tanks rated to supply building as well as critical services of that particular POD. The 4000A busbar comprising 3-phases, N & PE has minimal length and the N-PE is solidly grounded. The MV supply is from two independent 11kV REC supplies bussed on an open-ring to each transformer (not shown).

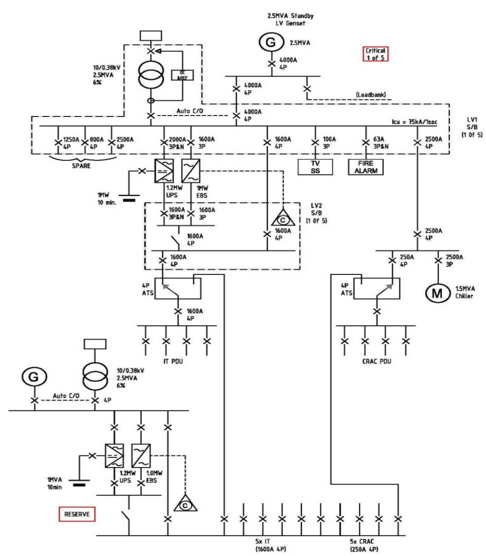

Fig 3.

Figure 3. Single line diagram showing LV generators installed in a Tier 3 Datacenter.

Contrast this to **Figure 4** showing a tier 4 data centre. Here parallel configured MV sets are bussed onto a 3-wire MV supply feeding a N/O ring connecting three ring main units supplying a dual redundant UPS system. The gensets are containerized externally some distance away from the data centre. The cost of distributing LV busbars over this distance would be prohibitive and despite extra cost of MV generators and switchgear it works out cheaper for this plant to distribute MV rather than LV. As before distribution transformers are cast resin and packaged within the LV switchboards. A 3-wire MV set with a delta winding requires an earthing transformer as it becomes islanded in the event of mains failure. Alternatively LV sets could be used with 'inverted' distribution transformers to supply the MV. The highest commercially available MV sets are rated at 13.8kV for the US market. Mainland Europe is usually 10/11 & 20kV, the latter requiring LV sets and step-up transformation. Clearly for such applications plant operators and Facilities Management have specialized training.

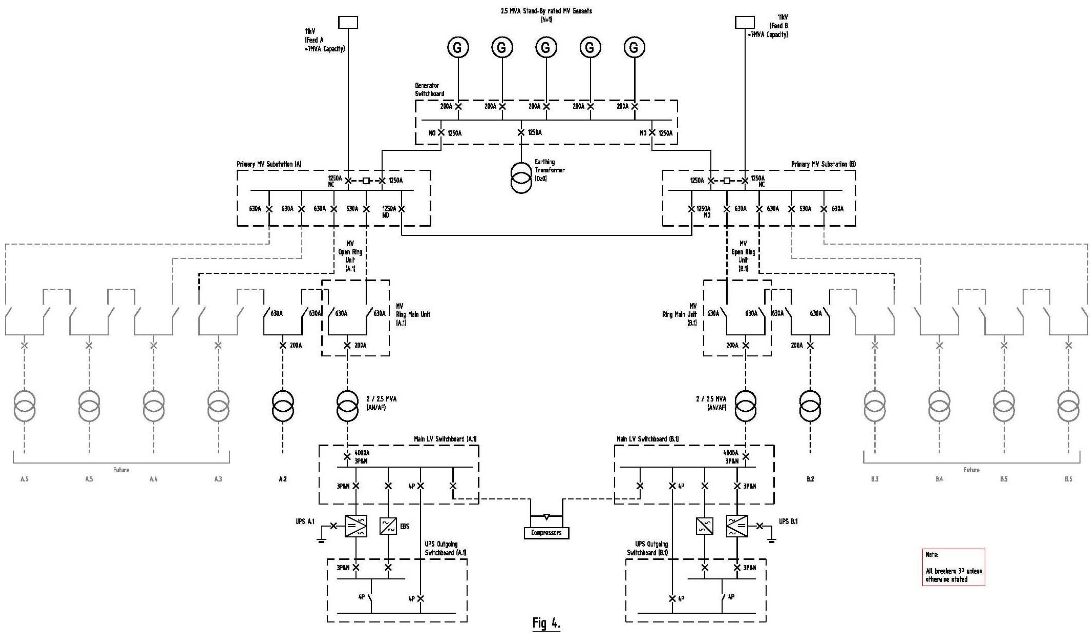

Figure 4. Single Line Diagram of a Tier 4 Datacenter

About the author:

John Boyle is Senior Applications Engineer in EMEA for APC by Schneider Electric. He is responsible for Electrical Engineering of critical power installations of large enterprise projects up to several MVA capacities.
John has over thirty years experience in power electronics (R & D) and electrical engineering (application), has a Bachelors degree in Physics from Newcastle University in 1973 and is a Chartered Electrical Engineer.

References:

M. Whitworth of Newage International Ltd (private correspondence)

R. Patrick of Cummins Power Generation (private correspondence)

L. L. J. Mahon, Diesel Generator Handbook, Pub: Butterworth-Heinemann