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# ELECTRICAL SYSTEM

# ALL YOU WANTED TO KNOW ABOUT SHORT-CIRCUITS BUT WERE AFRAID TO ASK!

## DESIGN REVIEW

Issue 1 Revision 1
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## Foreword

The short-circuit current analysis is a fundamental requirement of all regulatory agencies, classification societies and governmental bodies. Although the short-circuit condition is an abnormal operating state, the analysis is essential to ensure that a marine and offshore unit electrical system is designed with due cognisance to system and personnel safety.

There are several calculation methods available, some easy, some complex. It is important to understand that a method involving complex calculations may not produce any better results than one using simple approximations; particularly if the basic information required for the calculation is preliminary. The calculation methods tend to be very sensitive to the input data and consequently the quality of the result depends entirely on the quality of information available.

The calculation methods described in this design review fall into three broad categories; based on broad approximations, on basic generator and system data and based on full generator characteristics enabling short-circuit current decrement to be estimated. The correct method to use may not always be easy to determine and like most engineering situations it is necessary to apply professional judgement to use the right "tool" at the right time. A general rule would be to apply the most simple method and approximations first; then make a judgement as to the need to complete a more extensive analysis. Generally once it is decided to complete an extensive analysis, the methods proposed by the International Electrotechnical Commission IEC 61363-1 will give the "best" result for the calculation effort required.

This design review takes a light hearted view of short-circuit current calculation methods describing the simplest up to the most complex suggested by IEC 61363-1. Any review of calculation procedures cannot escape undertaking some calculations and in the case of electrical calculations, generally involves vector mathematics. This review is no different however rather than deriving many of the formulae involved, the review only quotes the basic formula required to complete a short-circuit current calculation in an attempt to keep the mathematical proofs to a minimum.

A basic understanding of vector mathematics will help in understanding some of the processes described in Section 12 and on. A copy of IEC 61363-1 is essential to understand the methods described in Section 16 and on.

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# 1. Introduction

“Sure I can calculate the short-circuit current. I really don’t know what all the fuss is about – and I’m not even an electrical engineer” – the Chief shouted above the thud thud thud of his Sulzer super monster!

The calculation of short-circuit currents is easy – as is anything when you know how. But also one should not forget that a little knowledge is both dangerous and can be expensive; so perhaps we should look at this calculation a little closer!

# 2. Why do we need to calculate the short-circuit current anyway?

As with any item of equipment, it must be sized to be man enough to do its job. In the case of short-circuits we are interested in the physical size and electrical properties of fuses, circuit breakers, switches, bus bars and other equipment likely to experience the energy released by a fault. Equipment must be sized to either withstand the fault energy, or in the case of circuit breakers and fuses, to open and clear the fault current quickly and safely.

Circuit breakers and fuses are designed to detect abnormal overcurrents in an electrical system and open the circuit if an overcurrent occurs. A short-circuit is one condition that can cause an overcurrent and analysis of the short-circuit current conditions is one factor to be considered when designing or modifying a marine electrical system.

A short-circuit occurs when two or more energized conductors contact each other. This may be due to an accident; someone placed a wrench across the switchboard bus bars; or from a failure of conductor insulation. In marine systems, the *three phase short-circuit* condition generally causes the highest value of fault current to occur.

At the instant the short-circuit occurs, a very low impedance path is created through which the full generator or system voltage is applied. The resultant current will be many times greater than the normal circuit current and if the circuit is not opened and the current interrupted, extensive damage can occur that will often lead to a fire. Similarly if the device that opens the circuit is not designed to break the high current, several things may happen, all of which are detrimental to safety.

- The energy released by the current may cause the device to explode.
- The contacts opening the circuit may weld together, with the result that the current is not interrupted.
- The contacts may start to open; the current may re-establish itself across the contact gap causing an arc. The arc may ignite other material and lead to a fire.

It is important therefore to estimate or calculate the value of the prospective current likely to occur under short-circuit conditions and ensure that the devices provided to interrupt that current are rated to withstand and interrupt it.

Similarly it is important to ensure that devices connected in the short-circuit current path, for example motor starters, are adequately sized to withstand the short-circuit current for the time required for the protective devices to open.

## 3. The short-circuit current must therefore be related to the short-circuit path impedance and system power?

This is true, and is the fundamental logic applied to calculate the short-circuit current value.

Unfortunately we never know when and where a short-circuit will occur. Accordingly estimating the short-circuit path impedance can be very complex.

In addition, although the generator or system power may be known, other consumers on the system add to that power under short-circuit conditions. For example, as a motor decelerates, it acts like a generator and contributes to the power driving the short-circuit current. It is difficult to determine the likely number of motors or other consumers contributing power at the time the short-circuit occurs. Consequently to determine precisely the total power driving the short-circuit can be very difficult.

Apart from these complications, when a generator experiences a short-circuit current, it responds in a non-linear fashion. In effect the generator impedance changes as the short-circuit current develops; this again affects the short-circuit current at any point in time.

## 4. But there must be an easy way to do this calculation?

There are many “easy” ways to calculate the short-circuit current. Unfortunately as the calculating methods become easier, their accuracy gets less. Sometimes this is not important and does not affect the final choice of protection equipment. Sometimes however precise calculation is important in order to prevent existing equipment being discarded and replaced. It requires a degree of engineering judgment to determine the calculation methodology and extent of calculation necessary for any particular installation, and for any particular instance.

## 5. Don’t confuse me – just give me a simple calculation and let’s get on with the job!

That’s fine. The easiest short-circuit current calculation is to multiply the total generator full load current by 10 and add to it the total running motor current multiplied by 4, i.e.

10 x Sum of Generator Full load Current PLUS 4 x Sum of running motor current.

This will provide an approximate value of the *“Root mean square symmetrical short-circuit current”* or *“RMS Symmetrical short-circuit current*”, and may be used to specify the minimum short-circuit rating for all the electrical switchgear. This particular value defines the maximum *“breaking”* current of the switchgear.

A reasonable design strategy would be to then specify electrical switchgear that has a “standard” rating above this calculated value. Using this approach however you must ensure that the standard rating used, is standard for the specific country where it is intended to purchase the switchgear. Standards do vary from country to country. In general, North American standards are different from the rest of the world, but countries within North America generally follow the same standards. The North American standard rms symmetrical current ratings for low voltage circuit breakers are 14, 18, 22, 25, 30, 35, 42, 50, 65, 85, 100, 125, 150 and 200 kA

Electrical switchgear may be rated on a symmetrical current basis or an asymmetrical basis. It may be necessary therefore to determine other short-circuit values such as the *“average asymmetrical value”,* the *“maximum rms asymmetrical value”* or even the *“peak value*” of the short-circuit current.

The asymmetrical values can be obtained by multiplying the RMS symmetrical current calculated above by specific factors as follows:

- Average asymmetrical rms current = 1.4 x rms symmetrical current
- Maximum rms asymmetrical current = 1.8 x rms symmetrical current
- Peak asymmetrical current = 2.6 x rms symmetrical current.

An example illustrates the calculation:

> Calculate the short-circuit current for a tug and specify the switchgear ratings. The generators are 2 x 120 kW 0.8 power factor and may operate in parallel. The motor load is assumed to be 60 kW. The electrical system is 3 phase 440 volts.

The rms symmetrical current is calculated as follows:

Generator full load current = (120 x 1000) / (square root of 3 x 440 x 0.8) = 197 amps

Motor running current = (60 x 1000) / (square root of 3 x 440 x 0.8 x 0.9) = 109 amps. (This assumes that the motors are approximately 90 % efficient and are designed for 0.8 power factor).

- Therefore the RMS symmetrical current = 2 x 10 x 197 + 4 x 109 = **4,376 amps**.
- Therefore the average asymmetrical current is 1.4 x 4,376 = **6,126 amps**
- Therefore the maximum rms asymmetrical current is 1.8 x 4,376 = **7,877 amps**
- And the peak asymmetrical current is 2.6 x 4,376 = **11,378 amps**.

Switchgear rated at ***5,000 amps RMS symmetrical*** will be adequate for this installation.

This *easy* calculation procedure gives the main system circuit breaker rating. If it is necessary to calculate the circuit breaker ratings for a low voltage system connected through transformers, we need the transformer rating and its low voltage rated current.

The *rms symmetrical current* can be estimated by multiplying the low voltage current by 20. The asymmetrical current values may then be obtained by applying the same factors as above.

For example the RMS symmetrical current for a 3 phase 120 volt switchboard connected through a 30 kVA transformer would be:

- 20 x 30 x 1000 / (square root 3 x 120) = **2,887 amps**.

## 6. The above calculation hardly requires a rocket scientist, why should I ever look for more complications?

For most small installations, i.e. those with an installed generator capacity of less than 500 kVA the above calculation methodology is entirely satisfactory. Refining the calculation is unlikely to enable a lower rated switchgear to be used. However for larger installations, this simple calculation may result in over-rating the switchgear requirements.

It is important to understand that the above calculation method has used *"rules of thumb"*. The calculations include several assumptions and these may not be correct for your particular system. The most significant assumption is that of the "system" or generator characteristics.

As outlined above (in section 2) the major generator characteristic that determines the short-circuit current is its *impedance*. Unfortunately generators are not straightforward and the generator impedance changes under different generator operating conditions. Under short-circuit conditions, the generator impedance changes as the short-circuit develops with time. When rating switchgear, it is the impedance during the first few milliseconds of a fault that determines the short-circuit current values that are of interest.

The *easy* calculation above has assumed a particular generator impedance value and that only the highest values of short-circuit current needs to be calculated. This impedance is termed the *sub-transient impedance*. In the simple calculation above, the "worst case" sub-transient impedance likely to be encountered on a marine generator, has been assumed. If on your installation the generator sub-transient impedance is more than the "worst case", then the value of short-circuit current will be less.

Similar assumptions have been made for the motor contribution, but this is not as significant as the generator contribution.

## 7. So how can I calculate the short-circuit current specific to my generators – but I don't want to do anything complicated?

A simple calculation specific to your generators is possible – but first it is necessary to understand a little more about sub-transient impedance values.

As with most electrical calculations, the "key to success" is to use "Ohms law". Simply put, this states that the current in an electrical circuit is equal to the voltage driving that current, divided by the impedance restricting the current. Or in symbols:

$$I = V / Z$$

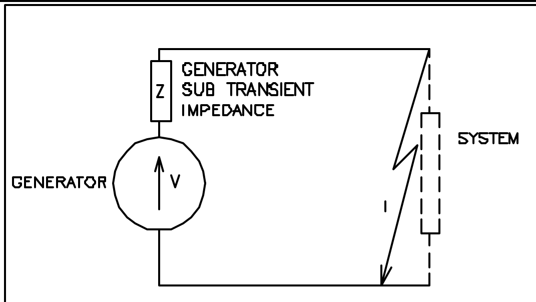

Fig 7.1 GENERATOR SHORT–CIRCUIT CURRENT

In the case of a short-circuit, we can assume that the voltage is the generator voltage. The impedance will be the sub-transient impedance of the specific generator used on the installation. This is illustrated in figure 7.1.
Again an example illustrates the method:

> Calculate the short-circuit current for a tug and specify the switchgear ratings. The generators are 2 x 120 kW 0.8 power factor and may operate in parallel. The motor load is assumed to be 60 kW. The electrical system is 3 phase 440 volts. The generator sub transient impedance is 12%.

The generator *short-circuit current* can be calculated using the formula:

$$\mathbf{I_{sc} = (100 \times I_g) / \%\ STI}$$

STI is the generator sub-transient impedance. To use this formula we need to calculate the generator full load current $I_g$ This may be provided by the generator manufacturer; if not, use the formula:

$$\mathbf{I_g = (1000 \times kilowatts) / (square\ root\ 3 \times volts \times power\ factor)}$$

For the example above, the generator full load current is therefore:

$$I_g = (1000 \times 120) / (1.732 \times 440 \times 0.8) = \mathbf{196.8\ amps}$$

The generator short-circuit current is therefore:

$$I_{sc\ g} = (100 \times 196.8) / 12 = \mathbf{1640\ amps}$$

The full short-circuit current can be calculated using the same methodology as the previous example using the generator *RMS symmetrical short-circuit current* of 1640 amps and the motor running current of 109 amps.

- Therefore the RMS symmetrical current = 2 x 1640 + 4 x 109 = **3,716 amps**.
- Therefore the average asymmetrical current is 1.4 x 3,716 = **5,202 amps**
- Therefore the maximum rms asymmetrical current is 1.8 x 3,716 = **6,689 amps**
- And the peak asymmetrical current is 2.6 x 3,716 = **9,662 amps.**

Again, switchgear rated at ***5,000 amps RMS symmetrical*** or above will be adequate for this installation.

Although when determining the circuit breaker short-circuit ratings, the end result is the same as determined in Section 5, (i.e. switchgear rated at 5,000 amps RMS symmetrical is adequate), the calculated values of short-circuit current are more appropriate to the actual system being investigated.

For this simple example one may question use of the added complication; but it should be noted that the calculated values are now some 17 % less than that previously calculated. If the first calculation had revealed short-currents close to, or even just above the standard switchgear ratings, then the second calculation is justified on the basis that it shows a 17% margin in the switchgear ratings and saves the use of a higher class of switchgear.

Again for this simple illustration, the cost difference between say 5 kA or 10 kA switchgear is small but such differences would be much more significant on a large installation.

## 8. But this last calculation does not seem to have used the ohms law formula?

Not entirely true – but a good observation!

The calculation method used in section 7 includes many simplifications and approximations. If this method is used, switchgear should be chosen with at least a 10% margin above the calculated value. That is, for a calculated *rms symmetrical current* of 3,716 amps, select switchgear the next rating above 4,088 amps. The following "ohms law" calculation will indicate why.

First convert the generator sub-transient impedance from a percentage value to an ohmic value. Again, rather than dwell on electrical theory, apply the following formulae blindly and leave the explanations to another time!

The sub-transient impedance in ohms = (the sub-transient impedance in % x (generator voltage)$^2$ x power factor) / (100,000 x generator kilowatts)

that is:

$$\textbf{STI in ohms} = (\%STI \times V^2 \times pf) / (100{,}000 \times kW)$$

For the example above,

Generator STI in ohms = (12 x 440 x 440 x 0.8 ) / (100,000 x 120 ) = **0.1549 ohms**

If we now apply ohms law, the short-circuit current for the generator will be:

$I_{scg}$ = 440 / 0.1549 amps, right? No, wrong! The generator STI in ohms is a "phase" value and accordingly we must use the "phase voltage" in the calculation. Therefore the generator short-circuit current $I_{scg}$ = 440 / (square root 3 x 0.1549) = 1640 amps as previously calculated – unfortunately this is still incorrect!

In the previous section (Section 7), figure 7.1 indicated that the generator voltage V drives the short-circuit current through the circuit. This is true, but the generator sub-transient impedance is internal to the generator, whereas V, or in our case 440 volts is the generator terminal voltage.

Therefore we must re-draw the circuit diagram and increase the internal generator driving voltage such that the terminal voltage is 440 volts. This means the generator internal voltage E will be V plus the voltage drop caused by the generator sub-transient impedance. Figure 8.1 illustrates this.

Instead of calculating the internal voltage precisely we can assume that it is about 10% higher than the terminal voltage and use the following formula to calculate the generator short-circuit current:

$$I_{scg} = 1.1\,V / (\text{square root } 3 \times \text{STR ohms})$$

In our case, $I_{scg}$ = (1.1 x 440)/ (1.73 x 0.1549) = **1804 amps**.

The asymmetrical short-circuit current values are calculated using the same factors as before.

Knowing that the sub-transient impedance is 12%, a more precise RMS symmetrical current calculation is:

**$I_{scg}$ = 1.12 V / (square root 3 x STR ohms)**

In this case this **$I_{scg}$** = (1.12 x 440)/ (1.73 x 0.1549) = **1837 amps**.

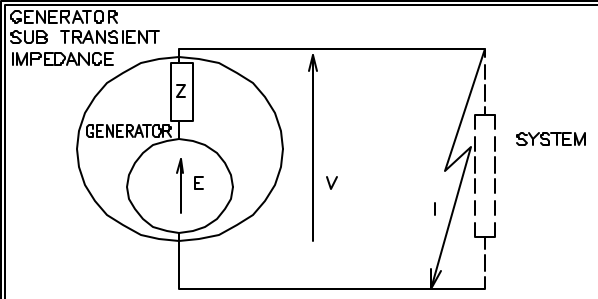

Fig 8.1 ACTUAL GENERATOR CIRCUIT

It is interesting to note that, these "more precise" calculations lead to values very close to the quick method outlined in the "10 times rule" and illustrated in section 4 above.

The results of the various methods are tabulated below:

| **CALCULATION METHOD** | **10TIMES RULE** SECTION 5 | **STI METHOD** SECTION 7 | **USING 1.1V** SECTION 8 | **USING 1.12V** SECTION 8 MODIFIED |
|---|---|---|---|---|
| GENERATOR RMS SYMMETRICAL SCC | 1970 | 1640 | 1804 | 1837 |
| MOTOR CONTRIBUTION AMPS | 436 | 436 | 436 | 436 |
| RMS SYM SCC AMPS | 4376 | 3716 | 4044 | 4110 |
| RATIO TO 10X RULE | 1 | 0.85 | 0.92 | 0.94 |

## 9. Won’t the circuit external impedance also reduce the short-circuit current?

Yes that is true.

The calculated short-circuit current at the generator switchboard, can be reduced by including the generator cable impedance. Similarly, the calculated short-circuit current at a distribution panel is reduced due to the feeder cable impedance between the switchboard to the distribution panel. The amount of the reduction is of course dependent upon cable size and length. A cable with a large cross sectional area has a small impedance and hence the reduction on the calculated short-circuit current is less than for a small cross section cable that has a large impedance.

Generally the generator cables are “large” and most times including generator cables has little effect on the final choice of circuit breakers. However for panel board feeder cables, this is not true and the cable impedance can often reduce the short-circuit level sufficiently to enable lower rated circuit breakers to be used.

For the previous example, including the generator cable and distribution panel cables will not change the circuit breaker rating. This is because the calculated short-circuit level is already well below the minimum standard ratings for 440 volt circuit breakers. This is generally the case for most tugs and small vessels with generators of this size.

## 10. So should I worry about cables?

For small vessels having installed generating capacities of up to about 500 kVA, 440 volts the complexity of the short-circuit current calculation is unlikely to change the choice of circuit breakers. In all probability standard 14 kA breakers or less will be applied throughout the installation and to include the effect of the cables would not be beneficial. An exception to this is if *miniature circuit breakers* can be used. In such cases, a calculation including distribution panel feeder cables will provide a better estimate of the feeder panel short-circuit current requirements. However for these small installations, generator cables are unlikely to cause a major change in circuit breaker requirements.

For installations rated 500 kVA - 1000 kVA, it may be worthwhile to include the effects of the cables. For installed capacities in the range 1000 – 1500 kVA and above, cables should be included in order to minimize the required circuit breaker short-circuit ratings at the distribution panels.

## 11. How do I calculate the Short-circuit current taking into account cables?

The calculation is easiest explained through an example.

> Calculate the short-circuit current for a cargo ship and specify the main switchboard switchgear ratings and the Engine Room Power Panel board ratings. The generators are 3 x 400 kW 0.8 power factor and all three can operate in parallel. The motor load is assumed to be 300 kW. The electrical system is 3 phase 440 volts. The generator sub transient impedance is 12%. The generator is

connected to the switchboard using 2 three conductor 500 MCM cable 5 meters in length. The Engine Room Power Panel is connected to the switchboard using 20 meters of 3 conductor #2 cable.

A diagram is useful!

Figure 11.1 shows the 3 - 400 kW generators connected to a switchboard with two 5 meter lengths of 3 conductor 500 MCM cable. The 300 kW of motor load is shown connected to the switchboard and an engine room power panel is connected with 20 meter of 3c #2 cable.

Although this example can be done using real ohmic values, it is easier to use a calculation method very familiar to electrical engineers; the “per-unit” or “percentage” method. The “per-unit” or “percentage” method changes all the values in the system to figures that are relative to a common base, such as 100, 500, or 1000.

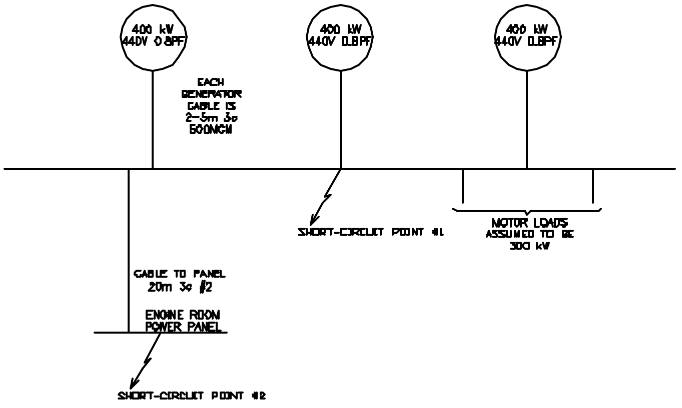

Fig. 11.1 SHORT-CIRCUIT CURRENT CALCULATION TAKING CABLES INTO ACCOUNT

The method simplifies the arithmetic. More importantly, the method is used in the electrical industry to define electrical equipment characteristics; for example the generator sub-transient impedance is generally expressed as a percentage value, say 12%. This is the value of the generator impedance “based” on the generator kilowatt or kVA rating. Rather than dwell on the mechanics of the method, its blind application is adequate to describe this short-circuit current calculation.

## Generator & cable impedances

For the generators, we already know that the impedance of one generator is 12% based on the 400 kW rating.

The generator cable is two 5 meter lengths of 3 conductor 500 MCM. For a 60 hz installation this cable has a resistance (R) of 0.069 ohms per kilometer and a reactance (X) of 0.092 ohms per kilometer. (These figures can be obtained from cable impedance tables).

The impedance of the cable is calculated as follows:

**Cable impedance $Z_c$ = Cable length L x Ö[ $R^2 + X^2$ ] per cable**

For two cables in parallel this becomes $Z_c/2$ i.e.

$$Z_c = (5/1000) \times \sqrt{}\ [0.069 \times 0.069 + 0.092 \times 0.092] = 0.00058 \text{ ohms}$$

i.e. $Z_{c/2}$ = **0.00029 ohms**

This ohmic value must now be converted to a percentage value using the same base as the generator impedance. In this case the "base" is the generator rating of 400 kW or 500 kVA (400/0.8).

Again, in order to circumvent a lengthy discussion on how to calculate percentage values, it is adequate to blindly apply a formula, which in this case is;

**Percentage impedance = [(100,000 x "base" kVA) / (Line Voltage)$^2$] x ohmic value)**

Hence for the generator cable, the percentage impedance is;

[(100,000 x 500) / (440 x 440)] x 0.00029 % = **0.0743%**

This value is now added to the generator impedance of 12 % to obtain the impedance of the generator and cable connected in series;

i.e. $Z_{(g+c)}$ = **12.0743%**

The above addition of impedances is not 100% accurate because it has not considered the resistive and reactive components of the impedance as separate entities. This simplification does affect the accuracy of the final result as will be seen later.

For three identical generators, the parallel impedance of the three generators is the impedance of one, divided by three. The combined impedance is therefore 12.0594/3 = **4.0248%**

Therefore applying the formulae used in 6 above the short-circuit current due to the generators is:

$I_{scg}$ = (100 x 656 ) / 4.0198 **= 16,299 amps**

## Motor load & its contribution to the short-circuit

For the motors there are two points to consider:

- Under short-circuit conditions, the motor operates as an induction generator on the system; therefore we can deal with it in the same way as a generator, i.e. an impedance in parallel with the system.
- Secondly, the motor load is a distributed load; i.e. it is not concentrated in one place as is the generator and hence its short-circuit current contribution is distributed through the system. At the main switchboard the contribution will be

different to that at a remote panel board. Furthermore, the amount of contribution to be included depends on the location of the short-circuit and the actual number of motors running just prior to the short-circuit. For faults at the main switchboard, the current contributed by a (series of) motor at a remote panel board will be affected by the impedance between the motor, panel board and the main switchboard where the motors are connected.

Again we must remember the accuracy of this method and apply a little system knowledge in our decision making. For this particular example, the majority of the “large” motors on the system that could be running will be connected to the main switchboard; therefore we will make the bold assumption that ALL the 300 kW of motors are connected to the main switchboard and are all running at the time of the short-circuit.

Now we must calculate the percentage impedance of the motor load. This is done by calculating the impedance of an “equivalent” generator on the system that would produce the same short-circuit current as the running motors.

We noted previously that the short-circuit current produced by a motor is approximately 4 times its running current. Therefore as calculated in 4 above the motor short-circuit current contribution is:

4 x 547 = **2187 amps RMS symmetrical**.

## Main switchboard short-circuit current

The main switchboard short-circuit current can be obtained by combining the generator and motor short-circuit current contributions, i.e.

The generator contribution is = 16299 amps
The motor contribution is 2187 amps

Therefore the generator and motor short-circuit current will be

16299 + 2187 = 18,486 amps

**i.e. 18.4 kA**

## Main switchboard circuit breaker rating

The problem now is how to use the above information to rate the main switchboard switchgear.

We know the calculation is “inaccurate” – but to what degree? The calculation result is just higher than the standard rating of 18 kA for 440 volt switchgear – should we use 18 kA gear or go one higher to 22 kA gear?

The “known” inaccuracies are the calculation of motor load, cable lengths and the physical quantities used for resistance, reactance and impedance. The motor load may have been excessive – but who knows precisely what the motor load will be when a fault occurs? The accuracy of the cable length is difficult to estimate, but the cable impedance is only about 0.5% of the generator impedance and so a 100% error here is unlikely to be consequential. The inaccuracies in the cable and generator physical values depends on the temperature at which the measurements were made and the temperature of the equipment at the time of the fault – difficult to guess! The generator impedance may be inaccurate to +/- 30% depending on where the value came from and hence the generator impedance could be as low as 8.4 % with a corresponding increase in the calculated short-circuit current.

We also know there is an inaccuracy in the calculating method itself. For example the short-circuit current calculation has used a "base" system and selected one of the generators for the base quantities. Therefore the voltage assumed will be the generator voltage of 440 volts; but this is incorrect as shown in Section 8 above. The voltage should have been the voltage behind the generator reactance, which is higher than 440 volts.

With all these uncertainties it is difficult to precisely quantify the accuracy of the above calculated value. It has been the author's practice to "assume" that the net sum of all inaccuracies will be at least 10 %, add this to the calculated value; then select the next highest value of switchgear. Therefore for a calculated value of 18.4 kA, the choice of 18 kA switchgear would be unwise and the next rating above 20.4 kA, i.e. 22 kA should be specified. This provides an approximate margin of 20 %, which is comfortable if somewhat conservative.

## Engine Room Distribution Panel short-circuit current

The Engine Room Distribution Panel (ERDP)is fed from the main switchboard using 20 meter of 3c #2 cable.

From tables, the cable resistance and reactance is $R_{(ERDP)} = 0.521$ ohms per km, $X_{(ERDP)} = 0.105$ ohms/km.

Therefore the impedance of 20 meters will be:

$$Z_{c\text{-}dp} = (20/1000) \times \sqrt{[(0.521 \times 0.521) + (0.105 \times 0.105)]} \text{ ohms, i.e. } \mathbf{0.01063 \text{ ohms}}$$

To calculate using percentage values, the ohmic impedance must be converted to the system base, as was done for the generator cables; i.e. based on 500 kVA

Again apply the formula;

$$\textbf{Percentage impedance} = [(100{,}000 \times \text{"base" kVA}) / (\text{Line Voltage})^2] \times \text{ohmic value})$$

Hence for the Engine Room Distribution Panel cable, the percentage impedance is;

$$Z_{(ERDP)} = [(100{,}000 \times 500) / (440 \times 440)] \times 0.01063 = \mathbf{2.7452\%}$$

To obtain the impedance at the ERDP, the cable impedance must be added to the combined impedance of the 3 generators, generator cables and motors.

We know that the short-circuit current due to the generators and motors is 18.49 kA, therefore we can calculate back to get the impedance, i.e.

$$18506.9 = (100 \times 656) / Z_{(g+c)(1,2,3,M)}$$

$$Z_{(g+c)(1,2,3,M)} = 100 \times 656 / 18{,}486 = \mathbf{3.5486\ \%}$$

Therefore adding the "impedances in series" gives:

$$Z_{(g+c)(1,2,3,M)(ERDP)} = Z_{(g+c)(1,2,3,M)} + Z_{(ERDP)} = 3.5486\% + 2.7452\%$$

$$\text{i.e. } Z_{(g+c)(1,2,3,M)(ERDP)} = \mathbf{6.2938\%}$$

Now the short-circuit current at the Engine Room Distribution Panel can be calculated as above using the formula:

$$\mathbf{I_{sc} = (100 \times I_g) / \% Z}$$

$$\text{i.e. } I_{sc} = (100 \times 656) / 6.2938 = 10{,}422.9 \text{ amps}$$

$$\mathbf{= 10.4\ kA}$$

## Asymmetrical short-circuit current values

The asymmetrical short-circuit current ratings can be obtained as previously by applying various multiplying factors; i.e.

- The RMS symmetrical current is as calculated above
- The average asymmetrical current is 1.4 times the RMS symmetrical current
- The maximum rms asymmetrical current is 1.8 times the symmetrical current
- And the peak asymmetrical current is 2.6 times the RMS symmetrical current

## ERDP Circuit Breaker Ratings

The inaccuracies outlined for the main switchboard fault level calculation apply equally to the ERDP calculation, however an inaccuracy of 10 % at the main switchboard only reflects as a 6% inaccuracy at the distribution panel. The main inaccuracies are due to the feeder cable length, resistance and reactance values. Again, it is prudent to apply a 10% margin and select the next highest switchgear rating, which for panel board circuit breakers would be 14 kA.

## The effect of including cable impedance

The purpose of this calculation was to show the effect of including cable impedance. It is clearly seen that by including the generator cable impedance, does not affect the choice of the main switchboard circuit breakers. However at the Engine Room distribution panel, the cables drastically reduce the calculated short-circuit level and circuit breakers two levels below that at the main switchboard, can be applied with confidence.

# 12. What about fault power factor, and surely cable impedance must affect current asymmetry

This is very true and raises several issues:

1. Is short-circuit power factor an issue?
2. What is asymmetry?
3. Will such calculations affect the bottom line choice of circuit breakers?

Each one of these topics could be the subject of several pages and rather than address them in detail, we will assume they *are* important, need to be addressed and worth at least a brief explanation!

### Short-circuit power factor

Short-circuit power factor is the power factor of the circuit when a short-circuit occurs. It is dependent upon all the circuit elements including resistance. The principal effect is on the voltage that develops across the circuit breaker contacts at the instance the circuit breaker opens. As the contacts part, the circuit current passes through zero. At this point, the arc across the circuit breaker contacts extinguishes and the current is broken. If there were only resistance in the circuit, the voltage when the current is zero, would also be zero. When there is inductance in the circuit, the instantaneous values of zero current and zero voltage occur at different points in time. Consequently, it is possible that when the current goes through zero, the voltage is reasonably high – and the arc re-establishes itself, with the net result that the circuit breaker does not do its job, may flash over or even blow up! Therefore an estimate of circuit power factor under short-circuit conditions is an important consideration.

Circuit power factor under short-circuit conditions must be considered when selecting circuit breakers. Reference to circuit breaker standards will show that when circuit breakers are tested under short-circuit conditions, the power factor corresponding to the circuit breaker breaking current is also recorded. Circuit breakers having ratings above 10000 amps symmetrical are generally tested with power factors from 0.15 to 0.3. Accordingly they should only be applied in circuits where the prospective short-circuit power is *equal to or greater* than this value. If the prospective power factor is less, there is a danger that the circuit breaker will not function correctly.

### Circuit asymmetry

Circuit asymmetry occurs when an electrical circuit contains elements other than resistance, such as the inductance of the generators and cables. It has a dynamic characteristic associated with it; the result being that whenever the current changes in a circuit due to switching, or short-circuits, a transient current occurs causing peak currents to be higher than those due to the resistive elements alone. The transient however does decay after a short period and the current settles into a symmetrical wave. The amount of asymmetry under fault conditions therefore depends on the amount of inductance caused by the generator and the distribution cables. Accordingly it is different at different points in the distribution system. The amount of asymmetry affects the instantaneous short-circuit current value; consequently it affects the multiplying factors that are applied to the symmetrical current to obtain the maximum asymmetrical and other circuit breaker ratings. Generally when taken into account, lower values of asymmetrical current will result.

## 13. How can I easily estimate power factor and ensure my circuit breakers function correctly

There are "simple" and rigorous ways to make an engineering assessment of the situation. Unfortunately, the "simple" methods require fairly lengthy electrical calculations and are in themselves subject to inaccuracies. Choice of method requires an engineering judgment based on experience and the available circuit breakers.

A short-circuit fault is analogous to a switch closing onto a resistive and inductive circuit. This causes an asymmetrical current to exist in the circuit. The asymmetrical current can be divided into two parts; a symmetrical part that is constant; and a part that decreases with time, down to zero. The symmetrical portion is often referred to as the "a.c. component" and its value depends primarily upon the generator and system characteristics. The decaying portion is often referred to as the “dc component”, and its value depends upon the instant in time that the short-circuit is applied.

The symmetrical component of the short-circuit current is calculated in a similar way to the previous example. Peak values and asymmetrical values are calculated using multiplying factors that are dependent upon the short-circuit power factor, rather than the fixed values quoted in 5 above.

The method of calculation can be illustrated using the previous example, i.e.

> Calculate the short-circuit current for a cargo ship and specify the main switchboard switchgear ratings and the Engine Room Power Panel board ratings. The generators are 3 x 400 kW 0.8 power factor and all three can operate in parallel. The motor load is assumed to be 300 kW. The electrical system is 3 phase 440 volts. The generator sub transient impedance is 12%. The generator is connected to the switchboard using 2 three conductor 500 MCM cable 5 meters in length. The Engine Room Power Panel is connected to the switchboard using 20 meters of 3 conductor #2 cable.

## Generator contribution

This time we need the generator resistance as well as its reactance. The resistance can be obtained from the manufacturer or from catalogue data. It is normally quoted as “$r_a$ “, the armature resistance. For generators of this size (400 kW), the armature resistance is of the order of 1.2%. Generator manufacturers can provide specific data for specific machines. Accordingly in order to assure the relevance of the short-circuit current analysis, such data should be considered as a contract requirement and provided to the designer before the system design is finalized.

For this example the sub-transient impedance of one generator is 12% based on the 400 kW rating. We can therefore use resistance of 1.2% to calculate the generator sub-transient reactance using the formula:

**The impedance (Z) = square root of {the resistance(R)$^2$ + the reactance(X)$^2$}**

The generator sub-transient reactance (generally written as x”) will be:

$$X'' = \sqrt{\{12 \times 12 - 1.2 \times 1.2\}} = 11.94\%$$

The generator cable is two 5 meter lengths of 3 conductor 500 MCM. As indicated in the previous example, for a 60 hz installation this cable has a resistance (R) of 0.069 ohms per kilometer and a reactance (X) of 0.092 ohms per kilometer. (These figures can be obtained from cable impedance tables).

The ratio of the resistance and inductance is important. Instead of calculating the percentage impedance directly we need to calculate the percentage resistance and inductance separately. These values are calculated exactly as previously for impedance; i.e. use the formula:

**Percentage value = [(100,000 x “base” kVA) / (Line Voltage)$^2$] x ohmic value)**

Hence for the generator cable, the percentage resistance is;

$$[(100{,}000 \times 500) / (440 \times 440)] \times 0.069 = \mathbf{17.82\%}$$

And the percentage reactance is;

$$[(100,000 \times 500) / (440 \times 440)] \times 0.092 = \mathbf{23.76\%}$$

Therefore for 5 meters of 2 runs of cable connected in parallel:

The resistance will be ½ x 5/1000 x 17.82% = **0.04455%**
And the inductance will be ½ x 5/1000 x 23.76% = **0.0594%.**

These values must now be added individually to the generator resistance and sub-transient reactance values to obtain the impedance of the generator and cable connected in series;

i.e. $R_{(g+c)} = 1.2 + 0.04455 = \mathbf{1.24455\ \%}$ and

$X_{(g+c)} = 11.94 + 0.0594 = \mathbf{11.9994\ \%}$

From these values we can calculate $Z_{(g+c)}$

i.e. $Z_{(g+c)} = \sqrt{\{1.24455^2 + 11.9994^2\}} = \mathbf{12.0638\%}$

For three identical generators, the parallel impedance of the three generators is the impedance of one, divided by three. The combined impedance is therefore = 12.0638/3 = **4.02126%**

The differences between this value and the values calculated in Section 11 are minimal and due to calculation rounding errors.

It should be remembered that the short-circuit current is a *vector* quantity and the resistive and reactive elements of the circuit will define the circuit power factor. The power factor can be calculated by dividing the resistance by the impedance, i.e.

Power factor = 1.24455 / 12.0638 = **0.1032**

Therefore the short-circuit current due to generators will be:

$I_{scc\ (g+c)(1,2,3)} = 100 \times 656 / 4.02126 =$ **16,313.3 amps at 0.1032 power factor**

This value comparable to that calculated in Section 11 (16,299 amps). In addition, we now know the power factor associated with this part of the short-circuit current.

## Motor load contribution

The motor contribution is dealt with in the same way as previously by considering all the motors connected to the main switchboard however we need to review the motor resistive and reactive components.

We previously established that the motor impedance equivalent to a short-circuit contribution of 4 times full load current is 25%. As a "general" rule of thumb, the ratio between motor sub-transient reactance and impedance is approximately 0.94, therefore the sub-transient reactance would be **23.5 %** and the resistance, **8.5%.** Again by dividing the resistance by the impedance, we can use these values to determine the power factor associated with the motor contribution; i.e.

Power factor = 8.5 / 25 = **0.34**

Therefore the motor contribution is;

$I_{scc(M)}$ = 4 x FLC i.e. 4 x 547 = **2188 amps at 0.34 power factor**

## Generator & motor short-circuit current

To obtain the short-circuit current at the main switchboard we need to add the generator and motor contributions.

| | | |
|---|---|---|
| The generator contribution is | $I_{scc\ (g+c)(1,2,3)}$ | = 16,313.3 amps at 0.1032 power factor |
| The motor contribution is | $I_{scc(M)}$ | = 2188 amps at 0.34 power factor |

As these values are both vectors, they must be added together using vector mathematics. The easiest way to do this is to use a calculator capable of changing "polar" coordinates into "rectangular" coordinates and adding together the "resolved" components; i.e.

$I_{scc\ (g+c)(1,2,3}$ = 16,313.3 amps at 0.1032 power factor =16,313.3 amps at 84.079 degrees i.e.

$$1{,}682.945 + j\ 16{,}226.258$$

If your calculator doesn't have these functions available, then it may be recalled that the two resolved components are actually equal to 16,313.3 cosine 84.079 and 16,313.3 sin 84.079.

Similarly for the motor

$I_{scc(M)}$ = 2188 amps at 0.34 power factor = 2188 amps at 70.0123 degrees i.e.

$$743.92 + j\ 2057.65$$

Adding together the resolved components we have

$$I_{scc(g+c)(1,2,3,M)} = (1{,}682.945 + 743.92) + j\ (16{,}226.258 + 2057.65) = (2426.865 + j\ 18{,}283.908)$$

If we now resolve this value back to polar coordinates we have;

$$I_{scc(g+c)(1,2,3,M)} = 18{,}444.27 \text{ at } 82.439 \text{ degrees}$$

## Power factor

Recalling that the power factor is in fact the cosine of the angle, then;

$I_{scc(g+c)(1,2,3,M)}$ = **18,444.27 at 0.1316 power factor**

This value is used for two purposes, one is to check the capabilities of the proposed circuit breakers by comparing this value to the circuit breaker test value, and secondly to calculate the asymmetrical short-circuit current values.

For the anticipated circuit breaker short-circuit current rating (i.e. 22 kA breakers), molded case circuit breakers are generally tested at 0.15 – 0.2 power factor. The standards do allow testing at a lower power factor and accordingly if the circuit breaker you wish to use has not been tested at a lower power factor, it would be prudent to check with the manufacturer that a prospective power factor of 0.13 is satisfactory.

## A Quickie

When completing detailed short-circuit current calculations it is difficult to escape vector mathematics. However when calculating the *main switchboard* short-circuit current on the average marine installation, the above result is very typical. Consequently for the level of accuracy obtainable using these methods, arithmetically adding the generator and motor short-circuit currents as illustrated in the previous example and *assuming* a power factor of 0.12 – 0.15 is generally quite acceptable.

More detailed calculations would be appropriate for installations when large bow thrusters or cargo pumps, with ratings comparable to one of the generators are powered from the main switchboard. Or alternatively if one or more of the generators are installed in say the forepeak, or other locations away from the main switchboard. In such instances the large motor load and generator cables will change increase power factor towards 0.15 or higher.

## Asymmetrical short-circuit current calculation – by formula

The asymmetrical values can be calculated either by applying a formula or by looking up the required "multipliers" from figures and tables such as Figure 11-1 in IEEE STD 45-1998 and Table 3 in the Transport Canada Marine Safety Code TP 127.

By formulae, it can be shown that for a resistive and inductive circuit, the asymmetrical current values at one half cycle of current are given by:

**Peak value $I_{pk}$ = Ö2 $I_{rms}$ { 1 + exp (-õ/ tan Ø)}**

**Asymmetrical RMS $I_{asy\ rms}$= $I_{rms}$ Ö { 1 + 2 exp (-2õ/ tan Ø)}**

**Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ = $I_{rms}$ [1/3 Ö { 1 + 2 exp (-2õ/ tan Ø)}+ 2/3 Ö { 1 + ½exp (-2õ/ tan Ø)}]**

Noting that cos Ø i.e. the circuit power factor is 0.1316 then tan Ø will be **7.53396**

Applying the above formula for this example we have:

Peak value = √2 $I_{rms}$ { 1 + exp (-∏/ tan Ø)} = √2 x 18,444.27 x { 1 + exp (-∏/ 7.53396)}

= √2 x 1.65903 x 18,444 = 43,274 amps = **43.3 kA**

Asymmetrical RMS $I_{asy\ rms}$= $I_{rms}$ √ { 1 + 2 exp (-2∏/ tan Ø)} = 18,444.27 √ { 1 + 2 exp (-2∏/ 7.53396)}

= 18,444.27 x 1.36698 = 25,213 amps = **25.2 kA**

Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ = $I_{rms}$ [1/3 √ { 1 + 2 exp (-2∏/ tan Ø)}+ 2/3 √ { 1 + ½exp (-2∏/ tan Ø)} ]

= $I_{rms}$ [0.45566+ 0.7355] = 18,444.27 x 1.19116 = 21,970 amps

**= 22.0kA**

Therefore we have calculated the following short-circuit current values for this example:

**Symmetrical RMS current $I_{scg}$ = 18.4 kA**

**Peak value $I_{pk}$ at 0.5 cycles = 43.3 kA = 2.35 x $I_{scg}$**
**Asymmetrical RMS current $I_{asy\ rms}$ = 25.2 kA = 1.37 x $I_{scg}$**
**Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ = 22.0 kA = 1.19 x $I_{scg}$**
**Short-circuit power factor = 0.132**

## Asymmetrical short-circuit current calculation – by table

As indicated above, the above values may also be calculated using tabular data based on the short-circuit power factor and circuit X/R ratios. For illustration, Figure 11-1 of IEEE 45 – 1998 will be used.

Based on an X/R ratio of **7.53396**, it can be estimated that $K_1$ = 1.195 and $K_2$ = 1.375 and therefore based on a Symmetrical RMS current $I_{scg}$ of 18.4 kA ;

Asymmetrical RMS current $I_{asy\ rms}$ = $K_2$ x 18.4 = 1.38 x 18.4 = **25.4 kA**
Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ = $K_1$ x 18.4 = 1.2 x 18.4 = **22.1 kA**

It can be seen that using Figure 11-1 of IEEE 45 – 1998 provides very comparable results.

## Engine Room Distribution Panel

The short-circuit current at the *main switchboard* due to the generator and motor contributions is given above as:

$$I_{scc(g+c)(1,2,3,M)} = \mathbf{18{,}444.27\ at\ 0.1316\ power\ factor}$$

This can be converted into an impedance using the formula quoted in section 7, i.e.

$$\mathbf{I_{sc} = (100 \times I_g) / \%\ IMP}$$

Therefore the percentage impedance is;

$$\mathbf{\%\ IMP = Z_{(g+c)(1,2,3,M)} = 100 \times 656 / 18{,}444.27 = 3.5567\%}$$

This impedance comprises both reactive and resistive parts. We can calculate the resistance by once more blindly applying some handy formula, in this case by multiplying the impedance by the power factor; i.e.

$$R_{(g+c)(1,2,3,M)} = 3.5567 \times 0.1316 = \mathbf{0.4681\%}$$

Consequently the reactance is given by:

$$X_{(g+c)(1,2,3,M)} = \sqrt{[\ \mathbf{Z}_{(g+c)(1,2,3,M)}{}^2 - R_{(g+c)(1,2,3,M)}{}^2]}$$

$$= \sqrt{[\ 3.5567^2 - \mathbf{0.4681^2}]} = \mathbf{3.5258\%}$$

Recall that the ERDP is connected to the Main Switchboard with 20m of 3c #2 cable for which the characteristics are:

Cable resistance is 0.521 ohms/km
Cable reactance is 0.105 ohms/km

Therefore for 20 meters of cable we have:

Cable resistance is 0.521 x 20/1000 = **0.0104** ohms
Cable reactance is 0.105 x 20/1000 = **0.0021** ohms
Cable impedance = **0.0106 ohms**

Converting these values to percentage figures gives;

Cable resistance = [(100,000 x 500)/(440 x 440)] x 0.0104 = **2.6911%**
Cable reactance = [(100,000 x 500)/(440 x 440)] x 0.0021 = **0.5424%**

By combining these values with the generator and motor impedance we can calculate the resistance and reactance at the ERDP, i.e.;

$R_{(g+c)(1,2,3,M,ERDP)} = 0.4681 + 2.6911 = \mathbf{3.1592\%}$
$X_{(g+c)(1,2,3,M,ERDP)} = 3.5258 + 0.5424 = \mathbf{4.0682\%}$

Therefore $Z_{(g+c)(1,2,3,M,ERDP)} = \mathbf{5.1508\ \%}$

## ERDP RMS symmetrical current calculation

This impedance value can now be used to calculate the rms symmetrical short-circuit current at the engine room panel board i.e:

$I_{sc\ ERDP} = (100 \times 656) / 5.1508 = 12{,}735.9$ amps = **12.74 kA**

It can be seen that this value is some 23% higher than that calculated previously.

## ERDP Power factor

The short-circuit power factor is given from;

$R_{(g+c)(1,2,3,M,ERDP)} / Z_{(g+c)(1,2,3,M,ERDP)} = 3.1592 / 5.1508 = \mathbf{0.6133}$

## ERDP asymmetrical short-circuit current

The “X/R” value is 4.0682/ 3.1592= 1.2877 Consequently the asymmetrical current values will be:

Peak value = $\sqrt{2}\, I_{rms} \{ 1 + \exp(-\Pi / \tan \varnothing)\} = \sqrt{2} \times 12{,}735.9\ \{ 1 + \exp(-\Pi / 1.2877)\}$
$= 1.5375 \times 12{,}736 = 19{,}582$ amps = **19.6 kA**

Asymmetrical RMS $I_{asy\ rms} = I_{rms} \sqrt{\{ 1 + 2 \exp(-2\Pi / \tan \varnothing)\}} = 12{,}735.9 \sqrt{\{ 1 + 2 \exp(-2\Pi / 1.2877)\}}$
$= 12{,}735.9 \times 1.0076 = 12{,}833$ amps = **12.8 kA**

Average 3 phase RMS $I_{3\ ph\ avg\ rms} = I_{rms} [1/3 \sqrt{\{ 1 + 2 \exp(-2\Pi / \tan \varnothing)\}} + 2/3 \sqrt{\{ 1 + \tfrac{1}{2} \exp(-2\Pi / \tan \varnothing)\}} ]$
$= I_{rms} [0.3359 + 0.66793] = 12{,}735.9 \times 1.00379 = 12{,}784$ amps
**= 12.8kA**

This time, if we use Figure 11-1 of IEEE 45 – 1998 for an X/R ratio of 1.2877, it will be noticed that there are no $K_1$ and $K_2$ values listed for this X/R ratio. Table 3 of Transport Canada Marine Safety Ship Electrical Standards

TP 127 also provide $K_1$ and $K_2$ values but again not for the x/r calculated on this installation. The closest values available are for an x/r of 1.3333, i.e. $K_1 = 1.004$ and $K_2 = 1.009$

Therefore based on a Symmetrical RMS Current $I_{scg}$ of 12.74 kA ;

Asymmetrical RMS current $I_{asy\ rms}$ = $K_2$ x 12.74 = 1.009 x 12.74 = **12.9 kA**
Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ = $K_1$ x 12.74 = 1.004 x 12.74 = **12.8 kA**

Using the TP 127 Table 3 multipliers again provides very comparable results.

## ERDP Short-circuit calculation summary

The calculated short-circuit current values for the engine room distribution panel are;

**Symmetrical RMS current $I_{scg}$ = 12.7 kA**
**Peak value $I_{pk}$ at 0.5 cycles = 19.6 kA = 1.53 x $I_{scg}$**
**Asymmetrical RMS current $I_{asy\ rms}$ = 12.8 kA = 1.008 x $I_{scg}$**
**Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ = 12.8 kA = 1.008 x $I_{scg}$**
**Short-circuit power factor = 0.613**

## Comparison between the "Impedance – Z Method" and "Resistance/inductance – X/R method"

We can now summarize and compare the results obtained by the two different calculation methods:

| **MAIN SWITCHBOARD** | **Z METHOD SECTION 11** | **X/R METHOD SECTION 13** |
|---|---|---|
| Symmetrical RMS current | 18.5 | 18.4 |
| Peak value $I_{pk}$ at 0.5 cycles | 47.5 | 43.3 |
| Asymmetrical RMS current $I_{asy\ rms}$ | 32.9 | 25.2 |
| Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ | 25.6 | 22.0 |
| Short-circuit power factor | UNKNOWN | 0.13 |
| **ENGINE ROOM DP** | **Z METHOD SECTION 11** | **X/R METHOD SECTION 13** |
| Symmetrical RMS current | 10.4 | 12.7 |
| Peak value $I_{pk}$ at 0.5 cycles | 27.0 | 19.6 |
| Asymmetrical RMS current $I_{asy\ rms}$ | 18.7 | 12.8 |
| Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ | 14.6 | 12.8 |
| Short-circuit power factor | UNKNOWN | 0.613 |

It can be seen that whereas the calculations at the Main Switchboard provide comparable results for the Symmetrical RMS current, at other locations, e.g. at the Engine Room Distribution Panel, the differences can be substantial. It can only be recommended that whenever it is necessary to calculate asymmetrical values, particularly at locations away from the main switchboard, a full calculation dividing the cable characteristics into their resistive and reactive components is preferred.

Again though we must remember the inaccuracies associated with these calculating methods. Of significance is that the symmetrical rms short-circuit current values have been calculated based on 440 volts – the system nominal voltage and not the generator internal voltage "behind" its sub-transient reactance.

Of equal significance is that the asymmetrical values are all calculated based on the *rms symmetrical value* calculated at time t = zero. But the asymmetrical calculations are all assume a value at the first 0.5 cycles of the short-circuit current.

The most significant issue is that the *rms symmetrical value* has been calculated *without* consideration of time; i.e. at fault initiation.

The quick response to the above is that the increase in short-circuit current due to the increased internal voltage of the generators, will probably be balanced by the reduction that would occur if the symmetrical rms current was also calculated at 0.5 cycles. An interesting response – but not one we can really "guarantee".

## 14. So what is the "truth" about short-circuit current calculations?

To understand the previous criticism, it is first necessary to understand what the symmetrical and asymmetrical values really are. This is easiest done through a picture!

Figure 14.1 shows the way a short-circuit current decays over a period of time. It is a time dependent, alternating, decaying asymmetrical current!

The asymmetrical current has a peak value $I_p$ and an RMS value $I_{asyrms}$

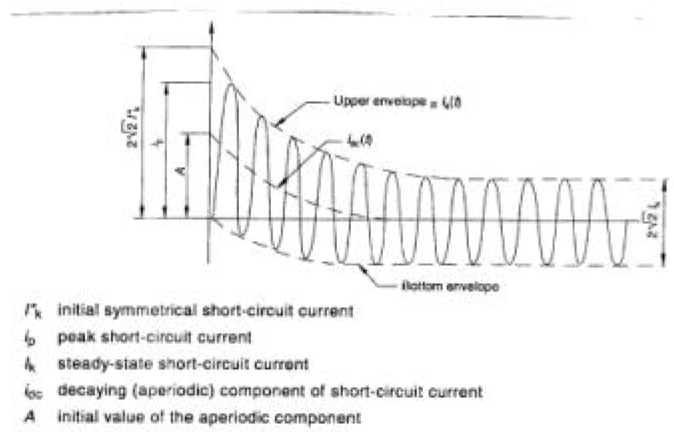

Fig 14.1 Short-circuit current decrement curve

The asymmetrical current can also be considered as a symmetrical alternating current,

$I_{ac}(t)$ that is displaced by a time dependent direct current, $I_{dc}(t)$.

The asymmetrical current $I_{asy}(t)$ is the sum of the ac and dc components.

If the dc component is removed from asymmetrical current, the resulting current is symmetrical as shown in Fig 14.2.

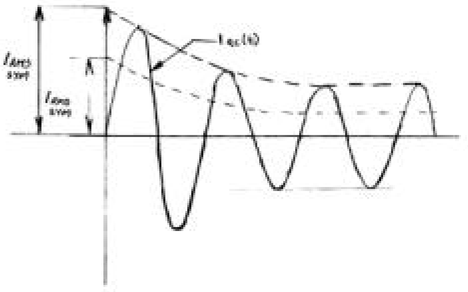

Fig 14.2 Symmetrical short-circuit current

The symmetrical RMS current calculated in the previous examples, i.e. using the sub-transient impedance, corresponds to that shown in Fig 12.2 and marked as $I_{IRM\ SYM}$

It can be seen that the RMS value corresponding to the maximum value during the first 0.5 cycle of fault current, is somewhat less. Accordingly, since the calculated asymmetrical current values are multiples of the symmetrical value, they too will be somewhat less than those calculated above.

## 15. Isn't it good that the "true" values are less than those calculated?

The answer is – it depends!

So far the short-circuit current calculations have assumed a single value for the generator sub-transient impedance. Unfortunately this is not true and can be seen by reviewing Fig 14.1. The short-circuit current decays over the first few cycles and then settles down to a steady value. Therefore the impedance must be increasing, or the internal voltage decreasing, or a combination of the two.

When calculating the short-circuit current at distribution panels installed several hundred meters from the main switchboard, e.g. a F'c'stle panel, the actual decay may not too important as the reduction in short-circuit current is mainly dependent upon the feeder cable impedance. However for the main switchboard and panels located close to it, that use circuit breakers that open in 0.5 cycle or less, the decay can affect the rating of circuit breakers installed.

For medium voltage installations, the circuit breakers generally do not operate until 3 cycles of short-circuit current have occurred. Accordingly the short-circuit current to be interrupted can be appreciably less than that calculated by any of the previous methods.

The short-circuit current decay during the first few cycles of short-circuit current occurs because the magnetic effects and saturation caused by the high initial values of short-circuit current affect the machine parameters. Electrical engineers have quantified these effects by considering the machine parameters over three distinct time periods; the initial values, referred to as the "sub-transient" values, the values following the sub-transient period, called the transient values, and the final values or those that occur in steady conditions, the steady-state values. The sub-transient and transient values are time dependent and have time constants associated with them, the sub transient and transient time constants.

## 16. OK – is there a calculation method that overcomes these problems?

For marine installations, the calculation methods of the International Electrotechnical Commission, IEC 61363-1 are perhaps the best available at this point in time; "best" meaning that the IEC formulae and methods use the minimum amount of calculation procedures and produce the lowest calculated values of short-circuit current that can be used with confidence to select circuit breakers and fuses. The IEC method also makes certain assumptions that introduce inaccuracies, however such inaccuracies are estimated to affect the result by less than 10%.

The IEC method is based on evaluating the *upper envelope* of the short-circuit current at discrete time intervals in order to obtain the maximum values. Having obtained the short-circuit current at the main switchboard, the values at other distribution panels are calculated similarly to that shown in 13 above, using cable resistance and reactance values to obtain the appropriate impedance value. In addition however, the change in circuit time constants that result from the additional feeder cable, is also included.

Motor loads may be considered either lumped at the main switchboard or divided through out the installation. Large motors are considered individually, treating the motor as a decaying exponential short-circuit current.

The basic formulae used to calculate the generator short-circuit current are:

$$I_{ac}(t) = (I''_{kd} - I'_{kd}) \exp(-t/T''_d) + (I'_{kd} - I_{kd}) \exp(-t/T_d) + I_{kd}$$

$$I_{dc}(t) = \sqrt{2}\,(I''_{kd} - I_o \sin \phi_o) \exp(-t/T_{dc})$$

The above formula describe the ac and dc components.

Consequently the current defined by the upper envelope, will be

$$I_k(t) = \sqrt{2}\, I_{ac}(t) + I_{dc}(t)$$

The values of $I''_{kd}$ and $I'_{kd}$ are dependent upon the sub-transient and transient impedances of the generator and the active internal machine voltage. The impedances may be obtained from the generator manufacturer. The voltages must be calculated from the nominal voltage of the machine increased to overcome the internal impedance. The voltages are therefore divided into sub-transient and transient values, and the proportion required to overcome the internal impedance depends upon the current operating in the system just prior to the short-circuit.

To ease the calculations, it is generally assumed that the machine was operating at full load prior to the short-circuit; this therefore ensures that the highest values of short-circuit current are calculated.

## IEC 61363-1 – an example

Instead of going through the calculation line by line, the previous example will be re-worked making reference to the above IEC standard formulae. IEC references are quoted as follows, IEC formulae (39) or IEC clause 6.3 etc.

Again the previous example will be used to illustrate the method, i.e.

> Calculate the short-circuit current for a cargo ship and specify the main switchboard switchgear ratings and the Engine Room Power Panel board ratings. The generators are 3 x 400 kW 0.8 power factor and all three can operate in parallel. The motor load is assumed to be 300 kW. The electrical system is 3 phase 440 volts. The generator sub transient impedance is 12%. The generator is connected to the switchboard using 2 three conductor 500 MCM cable 5 meters in length. The Engine Room Power Panel is connected to the switchboard using 20 meters of 3 conductor #2 cable.

To simplify the calculation, and for comparison purposes, it will be assumed that the entire motor load is concentrated at the main switchboard. This is generally in compliance with IEC clause 6.3.4 on the assumption that no motors are rated more than 100 kW.

## Data required

Additional generator data is required. This includes the generator sub-transient and transient reactance, resistance and time constants under saturated conditions. This information is generally available from the manufacturer.

For a 400 kW 0.8 pf 440 volt generator for the above example, typical values are:

Sub transient reactance $x''_d$ = 11.94% sub-transient time constant $t''_d$ = 12 ms
Transient reactance $x'_d$ = 15.00% transient time constant $t'_d$ = 80 ms
Resistance $r_a$ = 0.0046 ohms per phase; i.e. 1.2% on 500 kVA base
DC time constant $T_{dc}$ = 17 ms

## Generator and cable characteristics

Prior to calculating any short-circuit current, it is necessary to increase the values of generator resistance and reactance to include the cable characteristics.

This is the same as explained in previous examples and IEC clauses 8.2 illustrates the calculation. This must be done for both the transient and sub-transient impedance. Don't forget that prior to combining the generator and generator cable resistances and reactance values; they must be converted to the same base.

The sub-transient impedance becomes – resistance = 1.24% sub-transient reactance = **12.0%**
The transient impedance becomes – resistance = 1.24% transient reactance = **15.06%**

## Voltage driving the short-circuit current

As previously explained, the voltage that drives the short-circuit current is higher than the system voltage. The difference is due to the voltage drop caused by the generator internal resistance and reactance, and the current existing prior to the short-circuit occurrence. If the generator is operating at no load, the internal voltage and the terminal voltages will be equal, however as the load increases, so will the internal voltage hence causing an increase in the calculated short-circuit current.

The sub-transient and transient resistance and reactance are used to calculate the sub-transient and transient components of the generator's internal active voltages using IEC (5) and (6). Note that if the voltage at the main switchboard is to be considered as the "nominal" voltage, then the resistance and reactance values in these equations must also include the cable resistance and reactance.

In order to calculate "worst case" conditions, the preload current is considered as the generator rated current. Therefore the active voltages are;

The sub-transient active voltage $E''_{qo}$ becomes – **275.77 volts per phase**
The transient active voltage $E'_{qo}$ becomes – **280.99 volts per phase**

## Sub-transient and transient initial values of short-circuit current

The impedance and voltage data can now be used in IEC (3) and (4) to calculate the sub-transient and transient initial values of short-circuit current, i.e.

| | |
|---|---|
| Initial value of the sub-transient short-circuit current | $I''_{kd}$ = 5903.79 amps |
| Initial value of the transient short-circuit current | $I'_{kd}$ = 4802.48 amps |

## Short-circuit current ac and dc components

The initial values of short-circuit current are used to calculate the ac and dc components using equation (2). To do this, two other pieces of data are required, the time constants and the steady state current.

The time constants include the generator direct axis sub-transient, transient and dc time constants (obtained from the generator manufacturer) but modified to include the effects of the generator cables. IEC clause 8.2.2 b) describes how the cables can be included and IEC (93) (94) and (96) can be used to calculate the respective time constants, i.e.

Sub-transient time constant $T''_e$ = 12.04 ms; transient time constant $T'_e$ = 80.43 ms
DC time constant $T_{dce}$ = 16.52 ms

The steady state current generally depends on the type of voltage regulator used on the generator. For this example it has been assumed that the regulators are arranged to force the short-circuit current to a value not less than 3 times full load current i.e. $I_{kd}$ = 1968.24 amps. This occurs after the sub-transient and transient effects have died away.

The above values can now be substituted into IEC (2) and (9) to calculate the ac and dc components at a particular point in time. To align with the previous examples, the equation will be evaluated at the first ½ cycle of the short-circuit condition, i.e. 8.33 ms for a 60 Hz application. This gives:

$I_{ac}(t)$ evaluated at 8.33 ms = 5074.68 amps
$I_{dc}(t)$ evaluated at 8.33 ms = 4705.19 amps

For the three generators the ac and dc components at this point in time will be three times the above values, i.e.

3 x $I_{ac}(t)$ evaluated at 8.33 ms = 15,224.04 amps
3 x $I_{dc}(t)$ evaluated at 8.33 ms = 14,115.57 amps

## Motor load contribution

In order to include the motor contribution and calculate the short-circuit power factor it is convenient to calculate the impedance of a generator that would produce the above short-circuit current values, and combine that with the motor impedance.

Using the formulae of the previous sections, the impedance required to produce a short-circuit current of 15,224.04 amps is:

100 x 656.08 / 15,224.04 = **4.31%**

It can be reasonably assumed that although the reactance of the machine will change between fault initiation and 8.33 ms, the resistance of the generator and cable will stay constant at 1.24%, or 0.41 for the three generators operating in parallel.

Thus for an impedance of 4.31%, the reactance must be:

$$\sqrt{\{(4.31)^2 - (0.41)^2\}} = \mathbf{4.29\%}$$

The motor contribution was calculated in the previous example as;

Motor resistance = 10.2%; motor reactance = **28.20 %**

The three generator and motor impedances must now be combined to obtain the equivalent impedance of the parallel combination, i.e.

$$R_{(g+c)(1,2,3,M)} = \mathbf{0.48\%} \text{ and } X_{(g+c)(1,2,3,M)} = \mathbf{3.75\%}$$

Giving an impedance of **3.78%**

## Short-circuit power factor

The power factor can be calculated by using the formulae:

$$\text{Power factor} = R_{(g+c)(1,2,3,M)} / Z_{(g+c)(1,2,3,M)}$$

$$\text{i.e. } 0.48 / 3.78 = \mathbf{0.127}$$

## RMS Symmetrical short-circuit current

The RMS symmetrical short-circuit current at the ½cycle point may now be calculated as in the previous example; i.e.

$$I_{RMS\ SYM} = 100 \text{ X } 656 / 3.78 = 17{,}355 \text{ amps} = \mathbf{17.4\ kA}$$

## Asymmetrical short-circuit current

The “X/R” value is 3.75 / 0.48 = 7.81. Consequently the asymmetrical current values are:

$$\text{Peak value} = \sqrt{2}\, I_{rms} \{ 1 + \exp(-\Pi / \tan \varnothing)\} = \sqrt{2} \times 17{,}355\ \{ 1 + \exp(-\Pi / 7.81)\}$$
$$= \sqrt{2} \times 1.669 \times 17{,}355 = 40{,}959 \text{ amps} = \mathbf{40.96\ kA}$$

$$\text{Asymmetrical RMS } I_{asy\,rms} = I_{rms} \sqrt{\{ 1 + 2\exp(-2\Pi / \tan \varnothing)\}} = 17{,}355 \sqrt{\{ 1 + 2\exp(-2\Pi / 7.81)\}}$$
$$= 17{,}355 \times 1.37645 = 23{,}888 \text{ amps} = \mathbf{23.89\ kA}$$

$$\text{Average 3 phase RMS } I_{3\,ph\,avg\,rms} = I_{rms} [1/3 \sqrt{\{ 1 + 2\exp(-2\Pi / \tan \varnothing)\}} + 2/3 \sqrt{\{ 1 + ½\exp(-2\Pi / \tan \varnothing)\}} ]$$
$$= I_{rms} [0.45882 + 0.73746] = 17{,}355 \times 1.19628 = 20{,}761 \text{ amps}$$
$$= \mathbf{20.76kA}$$

## Main switchboard – summary of short-circuit current calculations

The calculated short-circuit current values at the main switchboard are;

**Symmetrical RMS current $I_{scg}$ = 17.4 kA**
**Peak value $I_{pk}$ at 0.5 cycles = 40.94 kA = 1.55 x $I_{scg}$**

**Asymmetrical RMS current $I_{asy\ rms}$ = 23.89 kA = 1.008 x $I_{scg}$**
**Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ = 20.76 kA = 1.004 x $I_{scg}$**
**Short-circuit power factor = 0.127**

## ERDP Short-circuit current calculation

In order to calculate the short-circuit current at the Engine Room Distribution Panel, the effects of the ERDP feeder cable must be included.

We can apply a similar methodology to that used previously.

The calculation considers the impedance of the "equivalent" generator as seen at the main switchboard, at ½ cycle of the short-circuit current and adds to this, the ERDP feeder cable impedance. The resulting resistance, reactance and impedance values are then used to calculate the symmetrical and asymmetrical values.

Note: this method is not precise as it does not take into account any change in decrement due to the feeder cable impedance.

As calculated above, the resistance and reactance values for the "equivalent" generator at ½ cycle point are;

$R_{(g+c)(1,2,3,M)}$ = **0.48%** $X_{(g+c)(1,2,3,M)}$ = **3.75%** $Z_{(g+c)(1,2,3,M)}$ = **3.78%**

And the ERDP feeder cable impedance is

Cable resistance = **2.691%** Cable reactance = **0.542%** Cable impedance = **2.745%**

Combining these figures gives;

$$R_{(g+c)(1,2,3,M,ERDP)} = 0.48 + 2.69 = 3.17\%$$
$$X_{(g+c)(1,2,3,M,ERDP)} = 3.75 + 0.54 = 4.29\%$$

Therefore $Z_{(g+c)(1,2,3,M,ERDP)}$ = **5.33 %**

This impedance value can now be used to calculate the rms symmetrical short-circuit current at the engine room panel board i.e:

$I_{sc\ ERDP}$ = (100 x 656) / 5.33 = 12,298 amps = **12.3 kA**

The power factor of the short-circuit current is given by;

$R_{(g+c)(1,2,3,M,ERDP)} / Z_{(g+c)(1,2,3,M,ERDP)}$ = 3.17 / 5.33 = **0.5948**

The "X/R" value is 4.29 / 3.17 = 1.353. Consequently the asymmetrical current values will be:

Peak value = $\sqrt{2}\, I_{rms} \{ 1 + \exp(-\Pi / \tan Ø)\} = \sqrt{2} \times 12{,}825 \{ 1 + \exp(-\Pi / 1.353)\}$
= $\sqrt{2}$ x 1.098 x 12,298 = 19,098 amps = **19.1 kA**

Asymmetrical RMS $I_{asy\ rms} = I_{rms} \sqrt{\{ 1 + 2 \exp(-2\Pi / \tan Ø)\}} = 12{,}298 \sqrt{\{ 1 + 2 \exp(-2\Pi / 1.353)\}}$
= 12,298 x 1.0096 = 12,416 amps = **12.4 kA**

Average 3 phase RMS $I_{3\ ph\ avg\ rms} = I_{rms} [1/3 \sqrt{\{ 1 + 2 \exp(-2\Pi / \tan Ø)\}} + 2/3 \sqrt{\{ 1 + ½ \exp(-2\Pi / \tan Ø)\}} ]$
= $I_{rms}$ [0.3365+ 0.6683] = 12,298 x 1.00479 = 12,357 amps

**= 12.4kA**

## ERDP Summary of Short-circuit current calculations

Therefore the calculated short-circuit current values at the ER DP are;

**Symmetrical RMS current $I_{scg}$ = 12.3 kA**
**Peak value $I_{pk}$ at 0.5 cycles = 19.1 kA = 1.55 x $I_{scg}$**
**Asymmetrical RMS current $I_{asy\ rms}$ = 12.4 kA = 1.008 x $I_{scg}$**
**Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ = 12.4 kA = 1.004 x $I_{scg}$**
**Short-circuit power factor = 0.595**

## Comparison of the "decrement" method with the previous short-circuit current calculations

The above values can now be compared with the previous calculations:

| MAIN SWITCHBOARD | | | |
|---|---|---|---|
| **SHORT-CIRCUIT CURRENT** | **Z METHOD SECT 11** | **X/R METHOD SECTION 13** | **INCLUDING GENERATOR DECREMENT** |
| Symmetrical RMS current $I_{scg}$ | 18.5 | 18.4 | 17.4 |
| Peak value $I_{pk}$ at 0.5 cycles | 47.5 | 43.3 | 40.94 |
| Asymmetrical RMS current $I_{asy\ rms}$ | 32.9 | 25.2 | 23.9 |
| Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ | 25.6 | 22.0 | 20.8 |
| Short-circuit power factor | UNKNOWN | 0.13 | 0.127 |
| **ENGINE ROOM DISTRIBUTION PANEL** | | | |
| **SHORT-CIRCUIT CURRENT** | **Z METHOD (SECT 9)** | **X/R METHOD** | **INCLUDING GENERATOR DECREMENT** |
| Symmetrical RMS current $I_{scg}$ | 10.4 | 12.7 | 12.3 |
| Peak value $I_{pk}$ at 0.5 cycles | 27.0 | 19.6 | 19.1 |
| Asymmetrical RMS current $I_{asy\ rms}$ | 18.7 | 12.8 | 12.4 |
| Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ | 14.6 | 12.8 | 12.4 |
| Short-circuit power factor | UNKNOWN | 0.613 | 0.595 |

It can be seen that by including generator decrement the calculated short-circuit current is reduced. The symmetrical RMS current is reduced by approximately 6.5 % and the asymmetrical current by 9.1%. If we were prepared to apply a 10% margin to the symmetrical current prior to choosing circuit breakers, then when calculating using decrement, this margin can be reduced. For this particular example, the bottom line may still be to use 22 kA circuit breakers at the main switchboard, but in some cases, using a decrement calculation may permit dropping one short-circuit level with confidence.

# 17. OK so will a decrement calculation give me the lowest short-circuit value that I can apply with confidence?

The answer is "Yes – but, we can perhaps do even better…". That is we can calculate a lower value with confidence and perhaps use lower rated, less expensive equipment on the system without compromising safety or reliability.

The above decrement calculation (Section 16) introduced a concept of an "equivalent" generator that produces the same short-circuit current as the three generators and motors on the system. The short-circuit current for each generator was calculated based on an exponential decay to obtain the current at the ½cycle point. The motor short-circuit current contribution was considered as a fixed value for the duration of the generator short-circuit current.

Unfortunately this methodology is only partly accurate! There are two aspects that affect the short-circuit current, particularly at the Engine Room Distribution Panel that we have not considered:

- Firstly the motor contribution is not a steady fixed value, but also decays with time. Furthermore at the instant of short-circuit, the voltage driving the *motor* short-circuit current, the internal voltage of the motor, is considerably less than the terminal voltage. Consequently the actual motor short-circuit current contribution during the first few milliseconds, may be some 15 – 20% lower at the ½cycle point, than that if it were assumed constant.

- Secondly the feeder cable resistance and reactance affect both the impedance to the short-circuit, and the ac and dc time constants. Therefore the generator short-circuit current decrement due to a fault at the ER DP will be lower in value and slower to decay as a result of the additional resistance and reactance.

## Motor load contribution including decay

IEC clause 5.1.2 Asynchronous Motors provides a calculation method that includes motor short-circuit current decrement. IEC clause 6.3.3 and 6.3.4 provides information on typical motor characteristics that can be used in the IEC clause 5.1.2.equations (11) to (21).

To compare methods, we will apply the IEC equations to the motor contribution used in the previous examples. The main difference between the IEC data and that used here is the amount of motor contribution considered. In North America, most regulatory bodies permit a motor contribution of 4 times full load current for the running motors, i.e. $Z_M$ = 25%; the IEC data assumes a 5 times full load current, i.e. $Z_M$ = 20%.

The previous examples (see section 11 & 13) used the following motor data:

Motor reactance $X''_M = 23.5\ \%$ Motor resistance $R_M = 8.5\ \%$
Motor impedance $Z_M = 25\%$.
Power factor = 0.8 and Motor efficiency = 90%
Motor power = 300 kW Motor full load current = 547 amps
Motor short-circuit current contribution = 4 x full load current = 4 x 547 amps

The motor time constants can be obtained from IEC clause 6.3.4 b) for 60 Hz, i.e. $T''_M = 18.67$ ms and $T'_{dcM} = 11.73$ ms

The sub-transient resistance and reactance are used to calculate the motor internal active voltage using IEC (18). In order to calculate "worst case" conditions, the preload current is considered as the motor's full load current; i.e. 547 amps. Therefore the active voltage is;

The sub-transient active voltage $E''_M$ is **203.91 volts per phase**

The impedance and voltage data can now be used in IEC (17) to calculate the sub-transient value of short-circuit current, i.e.

Initial value of the sub-transient short-circuit current $I''_M =$ **1756 amps**

The initial value of short-circuit current, together with the ac and dc time constants is used to calculate the ac and dc components. These values are substituted into IEC ((16) and (20) to calculate the ac and dc components at a particular point in time; i.e. to align with the previous examples, at the first ½ cycle (8.33 ms for 60 Hz) of the short-circuit condition, i.e.. This gives:

$$I_{acM}(t) \text{ evaluated at 8.33 ms} = \mathbf{1124\ amps}$$
$$I_{dcM}(t) \text{ evaluated at 8.33 ms} = \mathbf{1435\ amps}$$

The peak value can be calculated from IEC equation (21), i.e.

$$I_{pM} = \mathbf{3025\ amps}$$

In the previous calculation we determined that the ac and dc components at ½ cycle are

$$3 \times I_{ac(g1,2,3)}(t) \text{ evaluated at 8.33 ms} = \mathbf{15{,}224.04\ amps}$$
$$3 \times I_{dc(g1,2,3)}(t) \text{ evaluated at 8.33 ms} = \mathbf{14{,}115.57\ amps}$$

## Main switchboard short-circuit current including motor decrement

We can now add the generator and motor contributions to determine the ac and dc components of the short circuit current;

$$I_{ac(g1,2,3)M}(t) = 3 \times I_{ac(g1,2,3)}(t) + I_{acM}(t) = 15{,}224 + 1124 \text{ amps} = \mathbf{16{,}348\ amps}$$
$$I_{dc(g1,2,3)M}(t) = 3 \times I_{dc(g1,2,3)}(t) + I_{dcM}(t) = 14{,}116 + 1435 \text{ amps} = \mathbf{15{,}551\ amps}$$

And

$$I_{p(g1,2,3)M} = 3 \times I_{p(g1,2,3)}(t) + I_{pM}(t) = 35{,}646 + 3025 \text{ amps} = 38{,}671 \text{ amps} = \mathbf{38.7\ kA}$$

## Main switchboard asymmetrical short-circuit current including motor decrement

As indicated previously the peak value $= \sqrt{2}\, I_{rms}\, \{ 1 + \exp(-\Pi / \tan \varnothing)\}$

Therefore $38{,}671 = \sqrt{2} \times 16{,}348\, \{ 1 + \exp(-\Pi / \tan \varnothing)\}$ amps from which $\tan \varnothing = 7.92271$. Therefore power factor $= \cos \varnothing =$ **0.125** and the asymmetrical short-circuit currents are;

$$\text{Asymmetrical RMS } I_{asy\,rms} = I_{rms} \sqrt{\{ 1 + 2 \exp(-2\Pi / \tan \varnothing)\}} = 16{,}348 \sqrt{\{ 1 + 2 \exp(-2\Pi / 7.92271)\}}$$
$$= 16{,}348 \times 1.38019 = 22{,}563 \text{ amps} = \mathbf{22.6\ kA}$$

$$\text{Average 3 phase RMS } I_{3\,ph\,avg\,rms} = I_{rms}\, [1/3 \sqrt{\{ 1 + 2 \exp(-2\Pi / \tan \varnothing)\}} + 2/3 \sqrt{\{ 1 + ½ \exp(-2\Pi / \tan \varnothing)\}}\ ]$$
$$= I_{rms}\, [0.46006 + 0.73823] = 16{,}348 \times 1.1983 = 19{,}590 \text{ amps}$$
$$\mathbf{= 19.6kA}$$

## Main switchboard calculation summary including motor decrement

Therefore the calculated short-circuit current values at the main switchboard are;

**Symmetrical RMS current $I_{scg}$ = 16.4 kA**
**Peak value $I_{pk}$ at 0.5 cycles = 38.7 kA = 2.38 x $I_{scg}$**
**Asymmetrical RMS current $I_{asy\ rms}$ = 22.6 kA = 1.38 x $I_{scg}$**
**Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ = 19.6 kA = 1.20 x $I_{scg}$**
**Short-circuit power factor = 0.125**

## ERDP short-circuit current including motor decrement

In order to calculate the short-circuit current at the Engine Room Distribution Panel, the effects of the ERDP feeder cable must be included. As we are principally interested in this example to evaluate the effects of the *motor contribution decrement*, we can apply the same methodology as has been used in the previous example. For now we will neglect the decrement changes caused by the ERDP feeder cable impedance.

To complete the calculation we need to determine the impedance of the "equivalent" generator at the main switchboard at the ½ cycle point of the short-circuit current and add to it the ERDP feeder cable impedance. The resulting resistance, reactance and impedance values are then used to calculate the symmetrical and asymmetrical values. Note again however that this method does not take into account, any decrement change that results from the feeder cable time constant.

From the above calculations we determined that

$$\tan Ø = 7.92271$$
$$\cos Ø = 0.125$$
and the symmetrical RMS current $I_{scg}$ = 16.4 kA

Therefore at 440 volts, the impedance necessary to produce the above short circuit current will be:

$$(100 \times 656) / 16{,}348 = \mathbf{4.0127\%}$$

But cos Ø = 0.125 also = resistance / impedance; therefore the

Generator/motor combined resistance = 0.125 x 4.0127 = **0.5016 %**

Therefore the

Generator/motor combined reactance = $\sqrt{[4.0127^2 - 0.5016^2]}$ = **3.9812 %**

The ERDP feeder cable impedance is

Cable resistance = **2.691%** Cable reactance = **0.542%** Cable impedance = **2.745%**

Combining these figures gives;

$$R_{(g+c)(1,2,3,M,ERDP)} = 0.50 + 2.69 = \mathbf{3.19\%}$$
$$X_{(g+c)(1,2,3,M,ERDP)} = 3.98 + 0.54 = \mathbf{4.52\%}$$

Therefore $Z_{(g+c)(1,2,3,M,ERDP)}$ = **5.53 %**

This impedance value can now be used to calculate the rms symmetrical short-circuit current at the engine room panel board i.e:

$$I_{\text{sc ERDP}} = (100 \times 656) / 5.53 = 11{,}858 \text{ amps} = \mathbf{11.9\ kA}$$

The "X/R" value is 4.52 / 3.19 = 1.42. Therefore tan Ø = 1.42 and cos Ø = power factor = 0.5758.
Consequently the asymmetrical current values will be:

$$\text{Peak value} = \sqrt{2}\, I_{\text{rms}} \{ 1 + \exp(-\Pi / \tan Ø)\} = \sqrt{2} \times 11{,}858\ \{ 1 + \exp(-\Pi / 1.42)\}$$
$$= \sqrt{2} \times 1.109 \times 11{,}858 = 18{,}605 \text{ amps} = \mathbf{18.6\ kA}$$

$$\text{Asymmetrical RMS } I_{\text{asy rms}} = I_{\text{rms}} \sqrt{\{ 1 + 2\exp(-2\Pi / \tan Ø)\}} = 11{,}858 \sqrt{\{ 1 + 2\exp(-2\Pi / 1.42)\}}$$
$$= 11{,}858 \times 1.0119 = 11{,}999 \text{ amps} = \mathbf{12.0\ kA}$$

$$\text{Average 3 phase RMS } I_{\text{3 ph avg rms}} = I_{\text{rms}} [1/3 \sqrt{\{ 1 + 2\exp(-2\Pi / \tan Ø)\}} + 2/3 \sqrt{\{ 1 + \tfrac{1}{2}\exp(-2\Pi / \tan Ø)\}}\ ]$$
$$= I_{\text{rms}} [0.3373 + 0.6687] = 11{,}999 \times 1.00596 = 12{,}071 \text{ amps}$$
$$\mathbf{= 12.1kA}$$

## ERDP summary of short-circuit current calculations including motor decrement

Therefore the calculated short-circuit current values at the ER DP are;

**Symmetrical RMS current $I_{scg}$ = 11.9 kA**
**Peak value $I_{pk}$ at 0.5 cycles = 18.6 kA = 1.56 x $I_{scg}$**
**Asymmetrical RMS current $I_{\text{asy rms}}$ = 12.0 kA = 1.008 x $I_{scg}$**
**Average 3 phase RMS $I_{\text{3 ph avg rms}}$ = 12.1 kA = 1.017 x $I_{scg}$**
**Short-circuit power factor = 0.576**

## Comparison of motor decrement calculation to previous methods

These values can now be compared to the previous calculation:

| **MAIN SWITCHBOARD** | | | | |
|---|---|---|---|---|
| **SHORT-CIRCUIT CURRENT** | **Z METHOD SECTION11** | **X/R METHOD SECTION 13** | **INCLUDING GENERATOR DECREMENT SECTION 16** | **INCLUDING GEN & MOTOR DECREMENT SECTION 17** |
| Symmetrical RMS current | 18.5 | 18.4 | 17.4 | 16.4 |
| Peak value $I_{pk}$ at 0.5 cycles | 47.5 | 43.3 | 40.9 | 38.7 |
| Asymmetrical RMS current $I_{\text{asy rms}}$ | 32.9 | 25.2 | 23.9 | 22.6 |
| Average 3 phase RMS $I_{\text{3 ph avg rms}}$ | 25.6 | 22.0 | 20.8 | 19.6 |
| Short-circuit power factor | UNKNOWN | 0.13 | 0.127 | 0.125 |
| **ENGINE ROOM DISTRIBUTION PANEL** | | | | |
| **SHORT-CIRCUIT CURRENT** | **Z METHOD SECTION11** | **X/R METHOD SECTION 13** | **INCLUDING GENERATOR DECREMENT SECTION 16** | **INCLUDING GEN & MOTOR DECREMENT SECTION 17** |
| Symmetrical RMS current | 10.4 | 12.7 | 12.3 | 11.9 |
| Peak value $I_{pk}$ at 0.5 cycles | 27.0 | 19.6 | 19.1 | 18.6 |
| Asymmetrical RMS current $I_{\text{asy rms}}$ | 18.7 | 12.8 | 12.4 | 12.0 |

| | | | | |
|---|---|---|---|---|
| Average 3 phase RMS $I_{3\text{ ph avg rms}}$ | 14.6 | 12.8 | 12.4 | 12.1 |
| Short-circuit power factor | UNKNOWN | 0.613 | 0.595 | 0.576 |

It can be seen that with the latest values, we can confidently use 18 kA switchgear at the main switchboard and 14kA at the ERDP, and still know that we have a 10 % margin over the calculated short-circuit current value.

## 18. There is still another avenue to explore!

One of the main problems with the previous calculation methods is the evaluation of the asymmetrical short-circuit current based on a calculation of circuit impedance at ½ cycle. This methodology is correct in principal, but it contains a major flaw. The calculation uses the formulae, 100 x FLC / $I_{ac(g1,2,3)M}(t)$ at ½ cycle to determine the impedance of the motor/generator combination. By using this formula, the calculation assumes that the voltage behind the short-circuit current is constant and equal to rated voltage. We know that this is not the case, the voltage is higher.

IEC clause 7 considers the evaluation of an equivalent generator. The short-circuit current for the equivalent generator is evaluated from the individual generator and motor characteristics, which themselves consider the change in voltage from the sub-transient to the transient stage. The characteristics of the equivalent generator are then considered at one point in time and are *based* on the system *rated voltage*. Accordingly evaluation of the asymmetrical current using the equivalent generator impedance, will provide a more accurate assessment.

## 19. Evaluation of the short-circuit current using the IEC Equivalent Generator

The IEC Equivalent Generator method is based on the premise that the short-circuit current at any point on the electrical system can be evaluated by determining the characteristics of a single generator (or motor – but generally a generator) that produces the same short-circuit current as the individual machines it replaces.

The method requires a lot of reasonably complex calculations but it is useful when the system incorporates generators of different sizes, or generators and a large bow thruster, and the effects of the short-circuit current decrement must be considered.

As can be seen from the previous calculations, inclusion of the generator and motor short-circuit current decrement has enabled the required main switchboard rating to be reduced with confidence from 22 kA to 18 kA. In these examples the generators are all rated equally, and the equivalent generator approach was taken to evaluate the short-circuit current at the main switchboard. Use of the IEC Equivalent Generator methodology with these examples, will not reduce the short-circuit current at the main switchboard any further than that already determined. However if we can determine the characteristics of the equivalent generator, and then modify those characteristics to include the ERDP feeder cable impedance, it is likely that the calculated short-circuit current at the ERDP will be reduced. Unfortunately in order to determine if this can be advantageous, it is necessary to go through the complete Equivalent Generator calculation procedures. Although for the example we are using, 14 kA equipment (North American standard for this voltage) is likely to be used, we will complete the work both to illustrate the method and to determine the effects it has on the end result.

Again as previously, only the major steps using the IEC 61363-1 Clause 7 formulae will be noted here leaving the reader to confirm the results.

## Principal characteristics of the Equivalent Generator

The first step is to determine the principal characteristics of the generators and motors that will form the equivalent generator (EG).

For our example this comprises three 400 kW generators and 300 kW of motor load having a power of 333.3 kW from the system. Therefore the EG rating is;

3 x 400 + 1 x 333.33 = **1533 kW**

All machines are assumed to have an 0.8 power factor; therefore the EG has a kVA rating of;

**1917 kVA 0.8 pf**

## Calculating the constants M∗ and N∗

M∗ and N∗ are used to calculate the EG ac sub-transient and transient time constants. They are evaluated using the EG initial values of short-circuit current.

The EG short-circuit current at the main switchboard, both ac and dc components, comprises the sum of the individual generator and motor short-circuit current, at the main switchboard. This is defined by IEC equations (61) and (62).

The ac component of the EG short-circuit current is also defined by equation (63), which is the same format as that used for a "normal" generator in section 14 above, i.e.

$$I_{ac}(t)_* = (I''_* - I'_*) \exp(-t/T''_{d*}) + (I'_* - I_{k*}) \exp(-t/T'_{d*}) + I_{k*}$$

The subscript ∗ is added to indicate that the values apply to the EG.

$I''_*$ $I'_*$ *and* $I_{k*}$ are the initial values of the EG sub-transient, transient and steady state short-circuit current and can be evaluated by summing the initial values of each machine's sub-transient, transient and steady state short-circuit current. Therefore in this case we have;

For the generators – as described in section 16;

| | |
|---|---|
| Initial value of the sub-transient short-circuit current | $I''_{kd}$ = 5903.79 amps |
| Initial value of the transient short-circuit current | $I'_{kd}$ = 4802.48 amps |
| Steady state short-circuit current | $I_{kd}$ =1968.24 amps |

For the motors – as described in section 17

| | |
|---|---|
| Initial value of the sub-transient short-circuit current | $I''_M$ = 1756 amps |

Therefore for the EG

| | |
|---|---|
| Initial value of the sub-transient short-circuit current | $I''_*$ = 3 x 5903.79 + 1756 = 19,468 amps |
| Initial value of the transient short-circuit current | $I'_*$ = 3 x 4802.48 amps = 14,407 amps |
| Steady state short-circuit current | $I_{k*}$ =3x 1968.24 amps = 5,905 amps |

The above values can be used to calculate the two constants M∗ and N∗ using equations (68) and (69).

Therefore:

$$M_* = I''_* - I'_* = 19{,}468 - 14{,}407 = \mathbf{5061\ amps}$$
$$N_* = I'_* - I_{k*} = 14{,}407 - 5{,}905 = \mathbf{8503\ amps}$$

## EG sub-transient time constant

Equation (73) is used to calculate the EG sub-transient time constant. This equation requires evaluation of a function $K''(t)_*$ that is defined by equation (71). Equation (72) tells us that $K''(t)_*$ is also the sum of the function $K''(t)$ for each generator and the sum of $I''m \exp(-t/T''_M)$ for each motor. Equation (70) shows how to calculate

$K''(t)$ for each generator. It should be noted that there is an error in equation (70); $T''_{d*}$ is incorrect – this should be $T''_d$ .

Therefore we must first evaluate $K''(t)$ for each generator:

$$K''(t) = (I''_{kd} - I'_{kd})\exp(-t/T''_d) + I'_{kd}$$

This formulae is evaluated at the ½ cycle point, i.e. at $t = \Pi / 2$

From section 17 we know that;

Initial value of the sub-transient short-circuit current $I''_{kd} = 5903.79$ amps
Initial value of the transient short-circuit current $I'_{kd} = 4802.48$ amps
Sub-transient time constant $T''_e = 12.04$ ms
Transient time constant $T'_e = 80.43$ ms
DC time constant $T_{dce} = 16.52$ ms

Therefore for each generator:

$$K''(t) = (5904 - 4802) \exp(-8.33 / 12.04) + 4802 = 5354$$

Therefore for three generators;

$$K''(t) = 3 \times 5354 = 16{,}061$$

We can now evaluate $I''_m \exp(-t/T''_M)$ to include the motor contribution.

From section 17 we calculated the initial value of the sub-transient short-circuit current for the motor contribution, $I'm = 1756$ amps. Section 17 also lists the motor time constants using values from IEC clause 6.3.4 b) for 60 hz, i.e. $T''_M = 18.67$ ms and $T'_{dcM} = 11.73$ ms.

Therefore:

$$I''_m \exp(-t/T''_M) = 1756 \exp(-8.33 / 18.67) = 1124$$

And hence:

$$K''(t)_* = 16{,}061 + 1124 = \mathbf{17{,}185}$$

We can place these values in equation (73) to calculate the EG sub-transient time constant, i.e.

$$T''_{d*} = -t_x / \ln[(K''(t)_* - I'_*) / M*] = -8.33 / \ln[(17{,}185 - 14{,}407) / 5061] = \mathbf{13.89\ ms}$$

## EG Transient time constant

We must now calculate the EG transient time constant $T'_d$ at the same point in time, i.e. 8.33 ms.

Equation (76) is used to calculate the EG transient time constant. This equation uses the previously calculated constants $M*$ and $N*$ and requires evaluation $Iac(t_x)_*$ as defined by equation (75).

Equation (75) tells us that $Iac(t_x)_*$ is the sum of $Iac(t_x)$ (ac component of short-circuit current) for each generator and for each motor.

To obtain the time constant applicable to the ½cycle point, $Iac(t_x)$ must be evaluated for each generator and motor, at the ½cycle point.
From section 17 we know that the ac component of short-circuit current at ½cycle is;

$$I_{ac}(t) \text{ evaluated at 8.33 ms} = 5074.68 \text{ amps}$$

Therefore for the three generators the ac components at this point in time will be three times the above, i.e.

$$3 \times I_{ac}(t) \text{ evaluated at 8.33 ms} = 15{,}224.04 \text{ amps}$$

For the motors, the value calculated in Section 17 is:

$$I_{acM}(t) \text{ evaluated at 8.33 ms} = 1124 \text{ amps}$$

Therefore for the EG;

$$Iac(t_x)_* = 15{,}224 + 1124 = \mathbf{16{,}348\ amps}$$

Equation (76) also requires calculation of $I_{k*}$ which according to equation (67) is the sum of $I_{kd}$ the individual machine steady state currents. For the motors this is zero but for the three generators, we calculated $I_{kd}$ as 3 x FLC for each generator, i.e. 1968.24 amps. Therefore for three generators, the value is 3 x 1968 = 5905 amps, i.e. for the EG

$$I_{k*} = \mathbf{5905\ amps}$$

We have calculated values for $M_*$ and $T''_{d*}$ above. Therefore placing these values in equation (76) to calculate the EG transient time constant give:

$$T'_{d*} = -t_x / \ln \{[\ Iac(t_x)_* - (\ M_* \exp(-t_x / T''_{d*}) + I_{k*}\ )\ ] / N_*\ \} \text{ i.e.}$$

$$T'_{d*} = -8.33 / \ln \{[16{,}348 - (5061 \exp(-8.33 / 13.89) + 5905)] / 8503\} = \mathbf{80.33ms}$$

## Evaluating $T_{dc*}$ the dc time constant

The dc time constant is evaluated in a similar manner using equation (79).

Equation (79) requires calculation of $I_{dc}(t_x)_*$ which is given from equation (78) as the sum of $I_{dc}$ for each generator and motor forming the EG. (Note the error in equation (78), $I_{ac}(t_x)_*$ should in fact be $I_{dc}(t_x)_*$ ).

From Section 17, $I_{dc}(t_x)$ calculated at the ½cycle point is 4705.19 amps. Therefore for three generators, $I_{dc}(t_x)$ is 3 x 4705 = 14,116 amps

From Section 17, $I_{dcM}(t)$ calculated at the ½cycle point is 1435 amps.

Therefore for three generators and motor contribution,

$$I_{dc}(t_x)_* = 3 \times 4705 + 1435 = \mathbf{15{,}550\ amps}$$

$I''_*$ has been calculated previously in order to evaluate $M_*$ and is given above as

$$I''_* = 3 \text{ x } 5903.79 + 1756 = \mathbf{19{,}468\ amps}$$

Therefore substituting these values into equation (79) to evaluate $T_{dc*}$ gives:

$$T_{dc*} = -t_x / \ln [I_{dc} (t_x)_* / (\sqrt{2} I''_*)] = -8.33 / \ln [15,550 / (\sqrt{2} \times 19,469)] = \mathbf{14.58ms}$$

## The Equivalent Generator Impedance

The impedance of the EG, at the ½cycle point can be evaluated as described in IEC clauses 7.4.6 using equations (83), (84) and (85). These equations use the initial values of short-circuit current $I''_*$ , $I'_*$ and $I_{k*}$. Calculated above as:

| | |
|---|---|
| Initial value of the sub-transient short-circuit current | $I''_*$ = 19,468 amps |
| Initial value of the transient short-circuit current | $I'_*$ = 14,407 amps |
| Steady state short-circuit current | $I_{k*}$ = 5,905 amps |

(Note again an error in formulae (85), $I_*$ *should be* $I_{k*}$ )

It will be noted that equations (83) through (85) use the pre-fault voltage $U_0$ , which for this example is the system voltage of 440 volts. Therefore:

| | |
|---|---|
| Sub-transient impedance | $Z''_* = U_0 / \sqrt{3} \times I''_* = 440/(\sqrt{3} \times 19,468) = 0.0130$ ohms |
| Transient impedance | $Z'_* = U_0 / \sqrt{3} \times I'_* = 440/(\sqrt{3} \times 14,407) = 0.0176$ ohms |
| Steady state impedance | $Z_* = U_0 / \sqrt{3} \times I_{k*} = 440/(\sqrt{3} \times 5,905) = 0.0430$ ohms |

In order to obtain the corresponding resistance and reactance values, a constant $c_3$ must be evaluated using the equivalent generator dc time constant $T_{dc*}$ Equation (81) gives the formulae:

$$c_3 = 1/ (2 \times \Pi \times f \times T_{dc*} ) = 1/ (2 \times \Pi \times 60 \times 14.58/1000) = \mathbf{0.1819}$$

The constant $c_3$ can now be applied in equation (86) to obtain the EG sub-transient reactance and equation (80) to obtain the EG resistance $R_*$ These values may then be applied in equations (87) and (88) to obtain the transient and steady state impedance values – noting again that these values apply at the short-circuit current ½ cycle point only. Therefore we have:

$$\begin{aligned}
X''_* &= Z''_* /\sqrt{(1 + c_3^2)} &&= 0.0130 / \sqrt{(1 + 0.1819^2)} &&= \mathbf{0.0128\ ohms} \\
R_* &= c_3 \times X''_* &&= 0.1819 \times 0.0128 &&= \mathbf{0.0023\ ohms} \\
X'_* &= \sqrt{[Z'^2_* - R_*^2]} &&= \sqrt{[0.0176^2 - 0.0023^2]} &&= \mathbf{0.0175\ ohms} \\
X_* &= \sqrt{[Z_*^2 - R_*^2]} &&= \sqrt{[0.0430^2 - 0.0023^2]} &&= \mathbf{0.0429\ ohms}
\end{aligned}$$

## Equivalent Generator – Summary of Characteristics

We have now calculated all the parameters of the equivalent generator. It is useful to summarize these before proceeding further with the calculations:

EG Power = 1533 kW , 1917 kVA, 0.8 pf 2515 amps
Sub-transient time constant $T''_{d*}$ = 13.89 ms
Transient time constant $T'_d$ = 80.33ms
DC Time constant $T_{dc*}$ = 14.58ms
EG Resistance $R_*$ = 0.0023 ohms
EG Sub-transient reactance $X''_*$ = 0.0128 ohms

EG Sub-transient impedance $Z''_{*}$= 0.0130 ohms
EG transient reactance $X'_{*}$ = 0.0175 ohms
EG transient impedance $Z'_{*}$= = 0.0176 ohms
Steady state reactance $X_{*}$ = 0.0429 ohms
Steady state impedance $Z_{*}$= = 0.0430 ohms

These values may be used as described in IEC clause 5.1.1.5 to calculate the short-circuit current using equations (1) through (10) however this would only serve as a check to the calculations. As the information used to obtain these characteristics depends upon the calculated short-circuit current for the generators and motors that comprise the equivalent generator, such a calculation now is purely repetitive. Recall that the purpose of doing this work was to calculate the short-circuit at the ERDP.

## 20. Using the Equivalent Generator to calculate the short-circuit current at a remote panel board.

The Engine Room Distribution Panel is fed by 20 m of 3c # 2 cable. Recall for 20 meters of cable we have:

Cable resistance is 0.521 x 20/1000 = 0.0104 ohms
Cable reactance is 0.105 x 20/1000 = 0.0021 ohms
Cable impedance = 0.0106 ohms

These values can now be used to modify the EG characteristics. IEC clause 8.2 describes how to include the feeder cable resistance and reactance values with the equivalent generator values. Therefore when the feeder cable is included, the Equivalent Generator plus ERDP feeder characteristics become:

EG+ERDP Resistance $R_{*ERDP}$ = 0.0023+ 0.0104 = 0.0127 ohms
EG+ERDP Sub-transient reactance $X''_{*ERDP}$ = 0.0128 + 0.0021 = 0.0149 ohms
EG+ERDP Sub-transient impedance $Z''_{*ERDP}$= 0.0196 ohms

EG+ERDP transient reactance $X'_{*ERDP}$ = 0.0175 + 0.0021 = 0.0196 ohms
EG+ERDP transient impedance $Z'_{*ERDP}$ = 0.0233 ohms

EG+ERDP Steady state reactance $X_{*ERDP}$ = 0.0429 + 0.0021 = 0.045 ohms
EG+ERDP Steady state impedance $Z_{*ERDP}$ = 0.0468 ohms

Using equations (93), (94) and (95) we can calculate the new time constants, i.e.

Sub-transient time constant $T''_{d*ERDP}$ = 16.03 ms
Transient time constant $T'_{dERDP}$ = 103.15ms
DC Time constant $T_{dc*ERDP}$ = 3.08ms

In evaluating the equivalent generator, we assumed the voltage behind the short-circuit current was the system voltage 440 volts. As we have learnt previously if the generator is on load, the voltage will be higher than this. Therefore we must make the same assumptions here when calculating the decrement at the ERDP, i.e. that the EG is at no load in order that the internal voltage can be the same as the external voltage of 440 volts. Therefore using the above values substituted into equations (5) and (6) and assuming for the EG that the generator is at no load the active voltages are;

The sub-transient active voltage $E''_{qoERDP}$ is – 254.03 volts per phase
The transient active voltage $E''_{qoERDP}$ becomes – 254.03 volts per phase

The impedance and voltage data can now be used in IEC (3) and (4) to calculate the sub-transient and transient initial values of short-circuit current, i.e.

| | |
|---|---|
| Initial value of the sub-transient short-circuit current | $I''_{kdERDP}$ = 12,952.73 amps |
| Initial value of the transient short-circuit current | $I'_{kdERDP}$ = 10,882.56 amps |
| Steady state short-circuit current | $I_{kdERDP}$ = 5904.72 amps |

The above values can now be substituted into IEC (2) and (9) to calculate the ac and dc components at the first ½ cycle of the short-circuit condition, i.e. 8.33 ms for a 60 Hz application. This gives:

$I_{ac}(t)$ evaluated at 8.33 ms = 11,727 amps
$I_{dc}(t)$ evaluated at 8.33 ms = 1,220.50 amps

The peak value = $\sqrt{2} \times I_{ac}(t) + I_{dc}(t)$ = 17,805 amps

Furthermore the peak value is given by:

$$\text{Peak value} = \sqrt{2}\, I_{rms} \{ 1 + \exp(-\Pi/ \tan \varnothing)\}$$

Therefore $\tan \varnothing = -\Pi / \ln \{[\text{Peak value} / \sqrt{2}\, I_{rms}] - 1\} = 1.2041$ ; and $\varnothing$ = 50.3 deg. Hence the power factor $\cos \varnothing$ = **0.6389**

The asymmetrical values are calculated as before:

$$\text{Asymmetrical RMS } I_{asy\,rms} = I_{rms} \sqrt{\{ 1 + 2 \exp(-2\Pi/ \tan \varnothing)\}} = 11{,}727 \sqrt{\{ 1 + 2 \exp(-2\Pi/ 1.2041)\}}$$
$$= 11{,}727 \times 1.0054 = 11{,}790 \text{ amps} = \mathbf{11.79\ kA}$$

$$\text{Average 3 phase RMS } I_{3\,ph\,avg\,rms} = I_{rms} [1/3 \sqrt{\{ 1 + 2 \exp(-2\Pi/ \tan \varnothing)\}} + 2/3 \sqrt{\{ 1 + ½\exp(-2\Pi/ \tan \varnothing)\}} ]$$
$$= I_{rms} [1/3 \sqrt{\{ 1 + 2 \exp(-2\Pi/ 1.2041)\}} + 2/3 \sqrt{\{ 1 + ½\exp(-2\Pi/ 1.2041)\}} ]$$
$$= I_{rms} [0.33513 + 0.66757] = 11{,}727 \times 1.0027 = 11{,}758 \text{ amps}$$
$$\mathbf{= 11.75kA}$$

Therefore the calculated short-circuit current values at the ERDP are;

**Symmetrical RMS current $I_{scg}$ = 11.7 kA**
**Peak value $I_{pk}$ at 0.5 cycles = 17.81 kA = 1.52 x $I_{scg}$**
**Asymmetrical RMS current $I_{asy\,rms}$ = 11.79 kA = 1.005 x $I_{scg}$**
**Average 3 phase RMS $I_{3\,ph\,avg\,rms}$ = 11.75 kA = 1.003 x $I_{scg}$**
**Short-circuit power factor = 0.639**

### Comparison of EG calculation with previous methods

We can now compare these with the previous calculations:

**MAIN SWITCHBOARD**

| **SHORT-CIRCUIT CURRENT** | **Z METHOD SECTION 11** | **X/R METHOD SECTION 13** | **INCLUDING GENERATOR DECREMENT SECTION 16** | **INCLUDING GEN & MOTOR DECREMENT SECTION 17** | **EQUIVALENT GENERATOR METHOD SECTION 20** |
|---|---|---|---|---|---|
| Symmetrical RMS current $I_{scg}$ | 18.5 | 18.4 | 17.4 | 16.4 | 16.4 |
| Peak value $I_{pk}$ at 0.5 cycles | 47.5 | 43.3 | 40.9 | 38.7 | 38.7 |
| Asymmetrical RMS current $I_{asy\ rms}$ | 32.9 | 25.2 | 23.9 | 22.6 | 22.6 |
| Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ | 25.6 | 22.0 | 20.8 | 19.6 | 19.6 |
| Short-circuit power factor | UNKNOWN | 0.13 | 0.127 | 0.125 | 0.125 |

**ENGINE ROOM DISTRIBUTION PANEL**

| **SHORT-CIRCUIT CURRENT** | **Z METHOD SECTION 11** | **X/R METHOD SECTION 13** | **INCLUDING GENERATOR DECREMENT SECTION 16** | **INCLUDING GEN & MOTOR DECREMENT SECTION 17** | **EQUIVALENT GENERATOR METHOD SECTION 20** |
|---|---|---|---|---|---|
| Symmetrical RMS current $I_{scg}$ | 10.4 | 12.7 | 12.3 | 11.9 | 11.7 |
| Peak value $I_{pk}$ at 0.5 cycles | 27.0 | 19.6 | 19.1 | 18.6 | 17.8 |
| Asymmetrical RMS current $I_{asy\ rms}$ | 18.7 | 12.8 | 12.4 | 12.0 | 11.8 |
| Average 3 phase RMS $I_{3\ ph\ avg\ rms}$ | 14.6 | 12.8 | 12.4 | 12.1 | 11.8 |
| Short-circuit power factor | UNKNOWN | 0.613 | 0.595 | 0.576 | 0.639 |

## 21. Conclusions

There are many ways to calculate the short-circuit current for a marine electrical system, some very simple, others quite complex. The complexity of the calculation is not always a good guide as to the "worth" of the result that is produced. Some calculation methods involve extensive calculations, but the result obtained cannot be relied upon. Other methods that also involve extensive calculations, do not necessarily provide final results that are as equally reliable to those attained by less complex methods.

This design guide has outlined three broad calculation methods:

1. Based on the "10 times" rule or the generator sub-transient reactance
2. Based on "Ohms Law" and neglecting short-circuit current decrement as a function of time
3. Based on "IEC 61363-1" using an approximate estimate of the generator and motor short-circuit current decrements.

The “best” calculation method to use is difficult to determine and depends on the size of installation, the point of interest on the system and the purpose of the calculation.

For any installation having an installed generating capacity of 500 kVA or less at 440 V, or 300 kVA or less at 230 volts the “10 times” calculation method is generally adequate. The advice would be to try it and provided the result justifies the use of the minimum rated circuit breakers (10 or 14 kA at the main switchboard), then additional calculations would seem unnecessary.

The “ten times” rule calculation can be refined if the generator sub-transient reactance is known, however care should be taken to use the generator “internal” voltage and not the system voltage or the results will be inaccurately low.

For larger installations, it is strongly advised that a more complex method of calculation be used; if the “10 times” rule is used, the short-circuit current calculated values will result in vastly over rated switchgear being installed, with consequent increase in equipment costs.

The reduction in short-circuit requirements due to feeder cables can be significant, particularly for the lower rated feeders (e.g. 100 amps or less). Accordingly when calculating the short-circuit level at panel boards, distribution panels and other switchboards supplied from the main switchboard, the impedance of the feeder cables should be included. Account should be taken of both the feeder cable resistance and reactance otherwise the calculation results may be unacceptably low.

Calculation methods that include generator and motor short-circuit decrement will produce the lowest acceptable values of short-circuit current. Such methods are based on IEC Standard 61363-1. The amount of calculation required for these methods is much the same as for the “Z” and “X/R” methods described; but the results are significantly less. Furthermore the sensitivity of the calculations can produce widely differeing results for small changes in impedance values. Consequently the IEC methods are therefore preferred as they offer a more accurate calculation method and give “more value for calculation time (money)” than other methods.

For systems involving

- different sizes of generator, or
- generators at different voltages located on different switchboards,

the short-circuit current calculations at distribution and power panels that take into account current decrement are not straightforward.

Essentially there are two approaches,

- ignore the time constant changes resulting from the feeder cable impedance, or
- to take the time constant changes into account

The later calculation can be completed using the Equivalent Generator approach outlined in IEC 61363-1 Section 7.

For most “conventional” marine electrical systems, the Equivalent Generator method will involve extensive calculations and produce results marginally different from more simple methods.

For the majority of marine electrical systems used in the commercial marine industry, a calculation method based on IEC 61363-1 taking into account both generator and motor short-circuit current decrement will produce the lowest reliable calculated value for the short-circuit current. Even with this method, cognisance should be given to the accuracy of the data used in the calculation (sub-transient reactance tolerances etc.), in order to apply a calculation "error" margin to the result, particularly when choosing protection gear with rating close to the calculated values. The author generally applies a 5 – 10% margin to all calculated values.