REDUCING THE EFFECT OF CONSUMERS OWN PLANT DIPS AND DANGERS OF DIP PROOFING

By R R SLATEM Pr Eng., FSAIEE, BSc (RAND)

SYNOPSIS

Reduction of the effect of most supply system voltage dips is not within the control of the consumer. He can, however, take measures to reduce the consequences of faults within his own plant and even eliminate voltage dips for the majority of in-plant faults. Fast protection combined with earth-fault current limitation is the main line of attack. The paper discusses this approach and other measures that the consumer can consider for reducing the effect of dips, and adds a word of caution about the need for careful consideration of the consequences of dip proofing major motor loads at the plant design stage and, particularly, when retrofitting dip proofing.

KEYWORD INDEX:

DIP PROOFING, FAST PROTECTION, LIMITED EARTH FAULT CURRENTS

1. INTRODUCTION

When the 400 kV ESCOM lines to the Cape were equipped with series compensation, fault throwing tests to prove the protection performance caused serious and widespread industrial plant disruptions. These disruptions, in spite of the fact that the tests were no more severe than the inevitable lightning faults, stimulated ESKOM to produce and publish widely a technical memorandum on the subject of system voltage dips and the dip proofing of industrial plant (Ref 1) to highlight, and to encourage plant designers to take cognizance of the problem.

However many plants were still designed, particularly by overseas consultants, without making due allowance for brief system voltage dips, particularly in respect of PLC power supplies and associated control and measurement systems. Hopefully this open discussion on a most important topic will alert prospective users and designers of the need for, and the possible dangers of, dip proofing.

2. REDUCING THE EFFECT OF CONSUMERS' OWN PLANT DIPS

2.1 The Influence of Earth Fault Level and Protection Speed.

Apart from badgering the supply authority to do its utmost to reduce the probability and consequences of voltage dips by ensuring minimum tower footing resistances, providing high speed fault clearance for line, buslbar and transformer, etc., faults, there is little the consumer can do about supply system generated voltage dips.

While the majority of dips may arise on the supply system, a significant number of dips, on a National basis, occur within the plant of the consumers themselves and these not only adversely affect his plant, they can also adversely affect the plant of adjacent consumers fed from the same point of common coupling. It is therefore imperative that the consumers as a whole see to it that their house is in order, for their own good and for the benefit of their neighbors where faults on their system can affect those neighbors.

It would, obviously, be unreasonable to suggest that the consumer can prevent faults from occurring on his system, but he can definitely take steps to reduce the impact of the majority of faults by:

2.1.1 Limiting earth fault currents to the order of 300 - 500 A;

2.1.2 Providing fast and selective protection on all parts of his main distribution systems, including the busbars (ref 2), retrofitting this where necessary. Limiting earth-fault currents to this order of magnitude, combined with their rapid clearance, has several major advantages

2.1.3 EF damage (proportional to I^2t) is greatly reduced;

2.1.4 The amount of ionized gas or arc plasma produced by a flash-over is limited to a level where the probability of the flash-over spreading to other phases is negligible;

2.1.5 The flash danger to operating personnel is virtually zero;

2.1.6 The triangle of phase-to-phase voltages is scarcely affected in magnitude, it merely shifts its position relative to earth (and, by so doing, increases the sound phase voltages with respect to earth to phase-to-phase value).

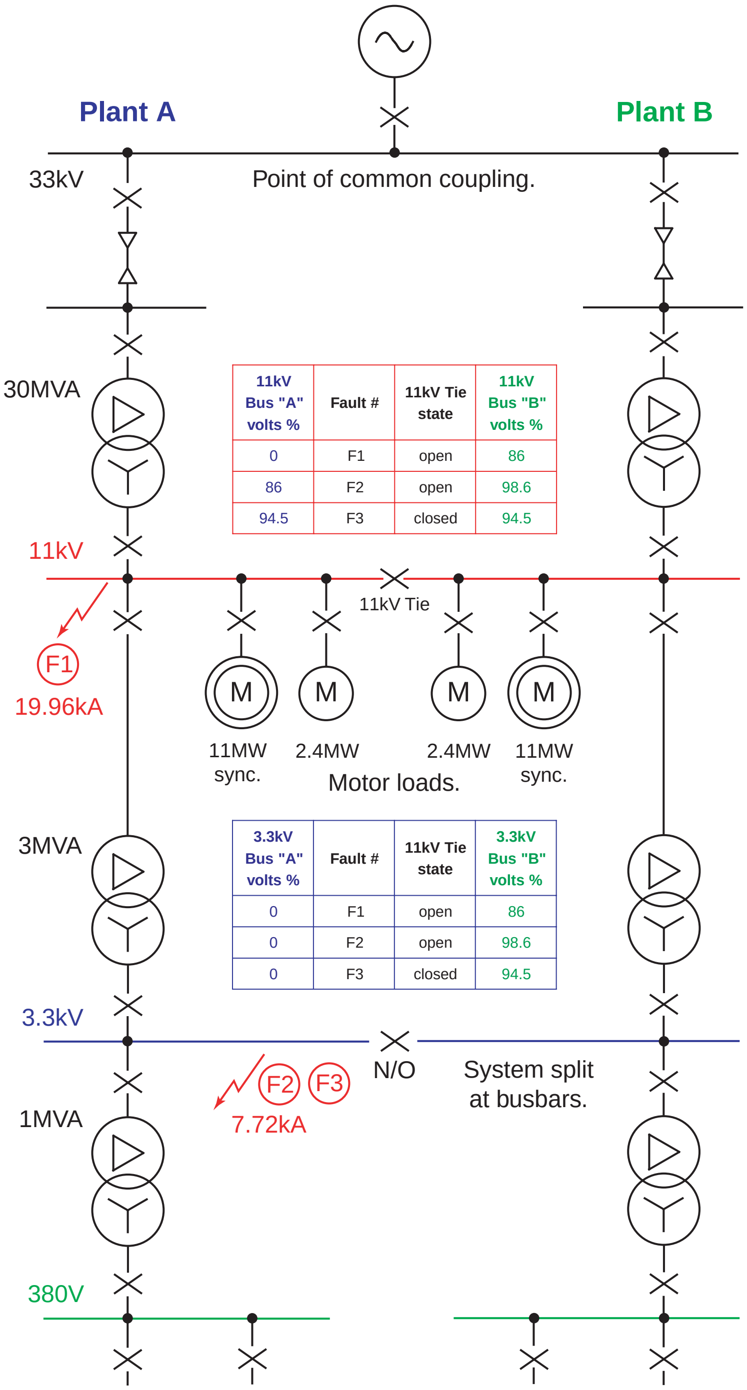
This combination of limited earth-fault current and fast clearance means that the most common faults probably 90% occur phase to earth do not result in a dip that would affect the plant. If the earth fault currents are not limited to a sufficiently low level (preferably below 600 - 800 A) and only delayed back-up protection is available for clearing them, there is considerably more danger to personnel and plant as the risk is high of the fault spreading to other phases with consequent increase of fault current level to the order of tens of kilo-amps. Inter-phase faults must inevitably lead to massive voltage dips, usually for extended periods of the order of 1 - 2 seconds (if only delayed over current & earth fault current is used), with severe consequences for operators, plant damage, stability and the interruption of production. The effect of such massive dips is often transferred through the supply transformers such that other areas of the plant and the associated supply system experience voltages too low in level and too prolonged for motor stability.

The moral is therefore, limit earth fault currents to a reasonably low level and clear them rapidly if you wish to avoid having unnecessary dips produced on your own plant.

2.2 The Influence of System Configuration

Another important mechanism often available to the consumer is to operate his system on a radial basis with the point of common coupling at as high a voltage level as possible. An example is shown in Fig 1, p3 where there are two independent halves of the plant, each with its own supply transformer and cable. The supply transformer and cable can, if required, supply both halves of the plant which can be coupled at 11 kV and 3,3 kV via tie breakers when required. We would recommend running with the tie breakers normally open and only closing them temporarily for load transfer or maintenance, or when excessive voltage dips must be avoided while starting large machines and a “stiffer” supply is needed.

With radial operation the point of common coupling is back at the 33 kV power station where the source impedance is low compared with the fault impedance, see Fig 2, p4 so the busbar voltage on one half of the plant is scarcely affected by a fault on the other half as shown by the % voltage readings on the diagram.



11kV Bus "A" volts %	Fault #	11kV Tie state	11kV Bus "B" volts %
0	F1	open	86
86	F2	open	98.6
94.5	F3	closed	94.5

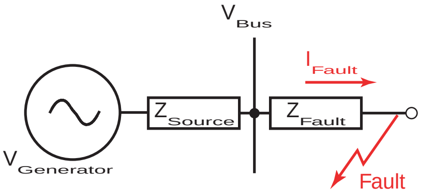
3.3kV Bus "A" volts %	Fault #	11kV Tie state	3.3kV Bus "B" volts %
0	F1	open	86
0	F2	open	98.6
0	F3	closed	94.5

Fig 1

Radial system reduces voltage dips.

2.3 The influence of normal system voltage level, shunt capacitors & synchronous machines.

If an instantaneous under voltage relay detects a sudden voltage decrease, some reduction of the extent and effect of the dip and improved post-dip recovery voltage can be effected by rapid switching on of all available shunt capacitor banks and filters and by invoking field forcing of any synchronous machines equipped with high-speed excitation systems. Also, by running the distribution system normally about 5% above nominal voltage, the apparent extent of the dip can be reduced marginally.



$$I_{Fault} = \frac{V_{Generator}}{Z_{Source} + Z_{Fault}}$$

$$V_{Bus} = I_{Fault} \times Z_{Fault} = V_{Generator} \times \left(\frac{Z_{Fault}}{Z_{Source} + Z_{Fault}} \right)$$

Hence for V_{Bus} to be high, >80%

$V_{Generator}$ must be as high as practical, 105%

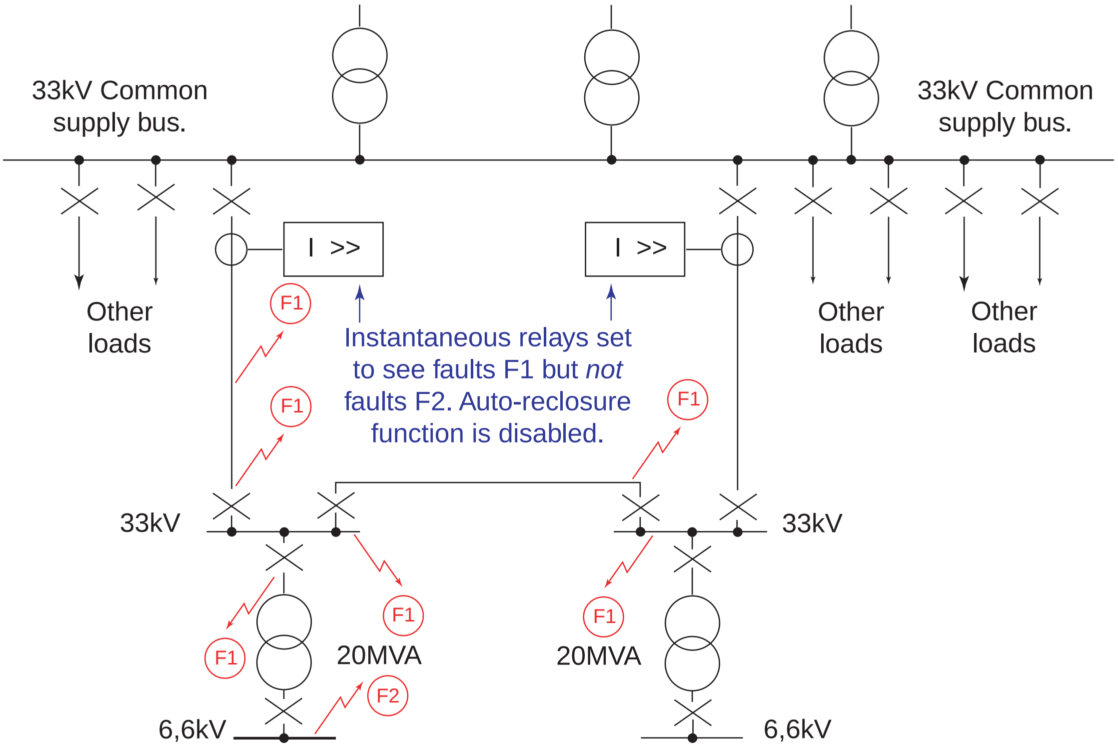
and the ratio $\frac{Z_{Source}}{Z_{Fault}}$ must be as small as possible <25%.

Fig 2

System network impedance distribution.

2.4 Distribution Systems with Overhead Lines

In some consumer distribution-systems, notably on 33 kV mining supplies, a significant number of overhead lines emanate from a common incoming supply busbar. Each pair of lines normally provides a ring supply to one or more loads, such as mine or ventilation shafts, see Fig 3. The lines are usually of the order of 2 - 5 km in length which makes the provision of pilot wire or other wire type unit protection, difficult to justify economically (to say nothing of the propensity of the local



Instantaneous relays set to see faults F1 but *not* faults F2. Auto-reclosure function is disabled.

Fig 3

Overlapping principle for overhead line networks with over current & earth fault protection & automatic re-closure.

inhabitants for helping themselves to the pilot cables). It is seldom possible to justify the provision of radio links so that selective high-speed cover for 100% of the line is normally not available. Consequently line faults are usually cleared by back-up relays in 1 - 1.5 seconds. This means that nearby line faults involving more than one phase (assuming a system with earth fault current limiting) will result in severe and prolonged supply busbar voltage dips that will probably cause all motor loads on all shafts fed from the common busbar to stall and require restarting with consequent inconvenience and possible loss of production. Line faults are usually transient in nature and supply is restored to the faulted section by auto-reclosing after sufficient delay (3 - 5 seconds) to allow the fault arc to deionize or any mechanical cause of the fault (e.g. bird, tree branch, wire thrown onto the line, etc) to fall clear. Where such auto-reclosing is used there is a simple and inexpensive method for reducing significantly the probability of prolonged dips caused by multi-phase line faults. To do this the protection must clear the fault rapidly enough to avoid the extensive loss of motor loads at other locations.

To achieve rapid clearance, the line over current and earth fault relays must be equipped with instantaneous “Hi-set” elements with their contacts brought out to terminals separate from those of the time-delayed “Lo-set” units. The Hi-set units are set so they cover as much of the length of the protected line as possible provided that they do not respond to faults (F2) on the lower voltage side of the next substation. It is often possible to set them so that they “overlap” the next line slightly. For a fault (F1) on the protected line, the next bus or the next line section, they trip rapidly and unselectively. Thus the duration of the dip in busbar voltage at the supply point is brief and other loads are relatively un-affected. When the line breaker/breakers on the faulted ring auto-reclose, the instantaneous trip is inhibited and a persistent fault (which is somewhat rare) is cleared discriminatively by the time-delayed protection. For this rare case only, the prolonged dip will usually affect other loads adversely but for possibly 85 - 95% of line faults, other loads will not be affected significantly.

The successful application of this so-called “overlapping” principle using Hi-set over current and earth fault depends on the fault levels, the line lengths and the size and impedance of the load transformers. Consequently it is not always possible to ensure fast “overlap” line fault clearance for all system-operating conditions. If the line protection is provided by distance relays, however, the successful application can be guaranteed as the distance relays measure the ratio of V/I and they can be set to operate very rapidly right down to fault currents of 20% the rated current and yet not “see” faults on the low voltage side of load transformers. Their operation is virtually independent of source impedance changes, the degree of overlap onto adjacent lines can be controlled with reasonable precision and even when the “overlap” is cut back during an auto-reclose, the instantaneous zone will cover at least the first 80% of the line so a high percentage of line faults will be cleared rapidly enough to avoid adverse effects on the other loads fed from the common busbar, despite source impedance and system operating configuration changes.

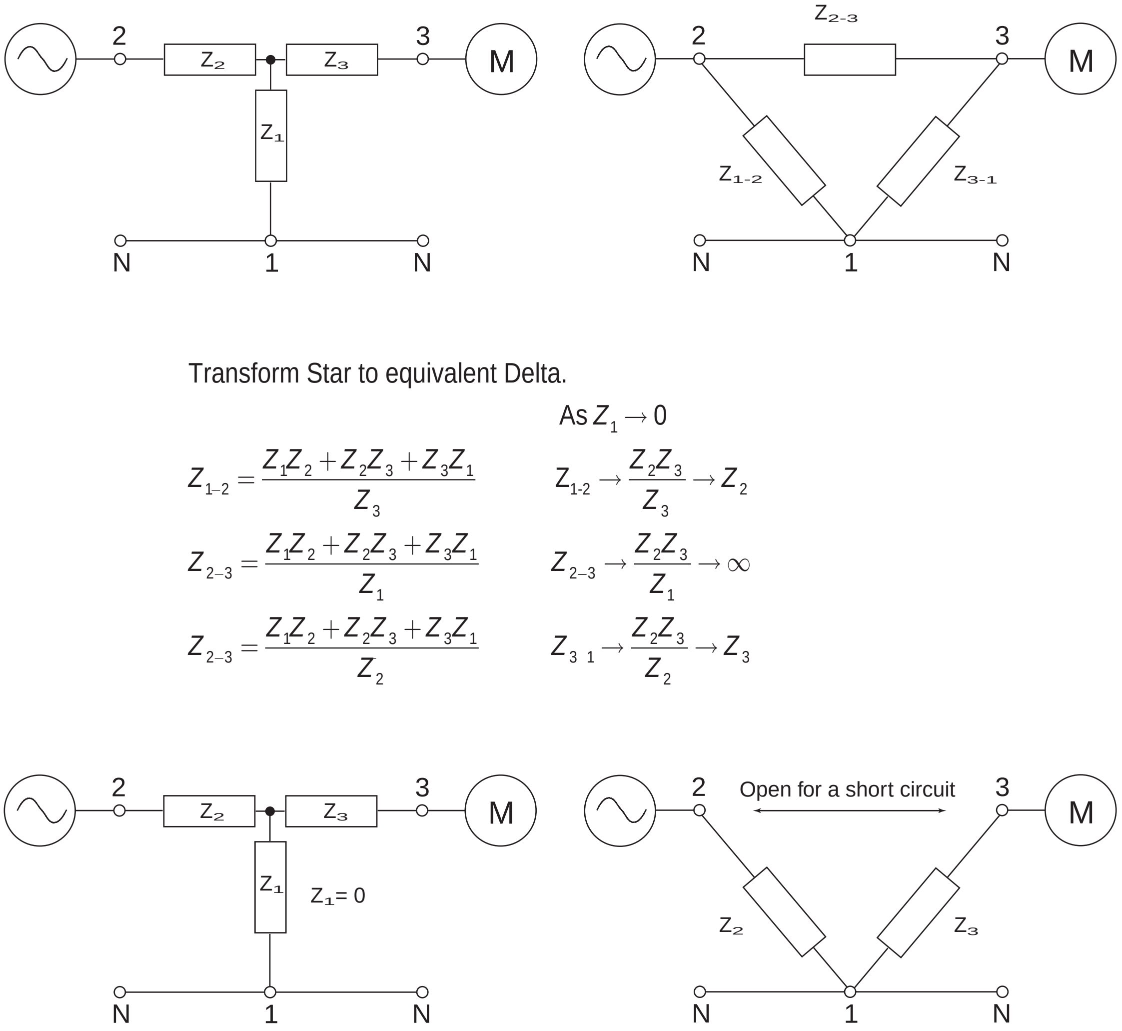
In South Africa the use of distance relays to protect medium voltage lines and cables has not been exploited, largely because of consumer fear of the unknown and of course, increased relay cost. Where they have been used, however, and the vastly improved performance of the protection and its simplicity of setting etc, is realized, the reaction of the user is one of enthusiastic acceptance. Other features of modern numeric distance relays such as fault location, analogue print-out of disturbance records etc, combined with better protection make this form of protection far more valuable than the old conventional directional over current and earth fault relays used on rings; and this at not too high a cost premium.

3 The Dangers of Dip Proofing

While it is obvious that dip proofing is essential if plant disruption and loss of production for inevitable system voltage dips are to be avoided, the requirement does not only affect the plant control functions. Motors and their associated drives can be subjected to excessive current surges and transient shaft torques when the system voltage recovers following a voltage dip, so those drives that must remain connected during a dip should be specified for this onerous duty at the design stage.

3.1 Winding forces and shaft torques.

When the system voltage dips to a low value, the motor, though remaining galvanically connected to the supply busbar, can behave as if it is completely disconnected from the actual power source, see Fig 4 below and, depending an the severity and duration of the dip, will experience a drop in speed with a consequent shift in the relative phase angle of its internal emf with respect to the supply, and an exponential decay of its internal voltage. A typical spiral response curve of internal voltage and phase angle with respect to the supply is shown in Fig 5, p7. If the



Transform Star to equivalent Delta.

As $Z_1 \to 0$

$$Z_{1-2} = \frac{Z_1Z_2 + Z_2Z_3 + Z_3Z_1}{Z_3} \qquad Z_{1\text{-}2} \to \frac{Z_2Z_3}{Z_3} \to Z_2$$

$$Z_{2-3} = \frac{Z_1Z_2 + Z_2Z_3 + Z_3Z_1}{Z_1} \qquad Z_{2-3} \to \frac{Z_2Z_3}{Z_1} \to \infty$$

$$Z_{2-3} = \frac{Z_1Z_2 + Z_2Z_3 + Z_3Z_1}{Z_2} \qquad Z_{3\ 1} \to \frac{Z_2Z_3}{Z_2} \to Z_3$$

Fig 4

Illustration of how a short circuit between motor & generator has the same effect as opening the circuit.

impedance to the fault causing the system dip is high compared with the motor locked rotor impedance, the motor internal emf can decay slowly and shift progressively in phase position (the flux being locked to the decelerating rotor). If the external fault Is removed and full system voltage thereby restored while the internal voltage is still high and approaching 180° out of phase with the system voltage, the “re-switching” motor re-acceleration current can approach 180% of the normal direct on line starting value. As the forces on the windings and the transient shaft torques are proportional to I^2, these can have values approaching 320% of normal. Consequently, to dip proof a drive not designed for reswitching could ultimately result in severe damage.

If the fault is close to the motor and the motor feeds appreciable short-circuit current to the fault, the demagnetizing effect of the lagging stator current will reduce the internal emf far more rapidly and the probability of high current reswitching surges is considerably reduced.

3.2 Tripping of Supply Transformers for post-dip Re-acceleration

In ref. 1 the importance of dip-proofing only essential drives is mentioned and this must be re-emphasized. It is generally neither possible nor desirable to set the overcurrent back-up relays so that they will not operate for a post-dip re-acceleration current surge if the load consists predominantly of motors and they are all

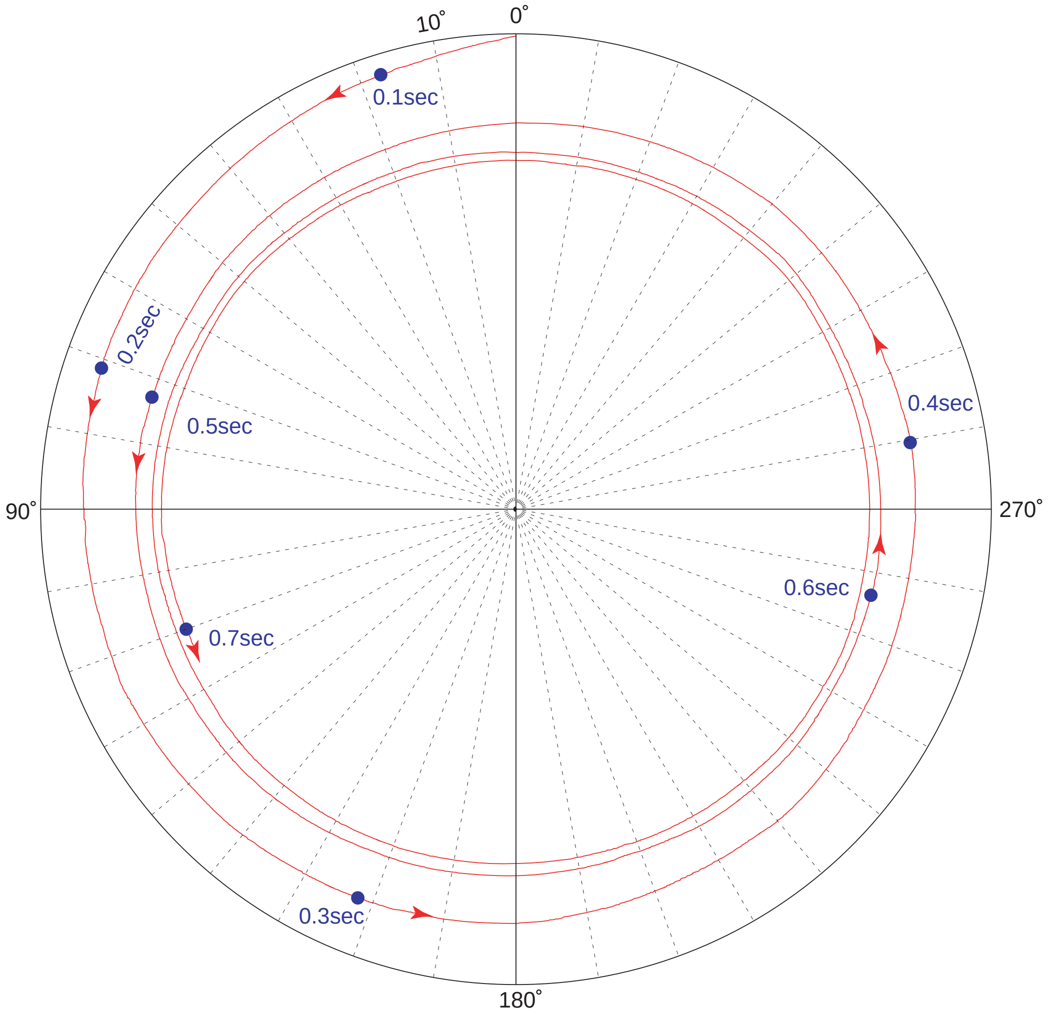


Fig 5

Variation of motor terminal voltage & angle relative to supply during a dip or outage.

dip-proofed. In such a case dip-proofing would be in-effectual as the load would be lost when the back-up relays tripped.

4. CONCLUSION

It is often possible for consumers to reduce the effect of in-house faults on their plant and that of their neighboring consumers by judicious choice of earthing level, protection speed and/or their normal system-operating configuration. Dip proofing should be applied only to vital drives and controls. These and their supplies must be designed to withstand the consequences of sudden restoration of voltage once a system fault is cleared, and the over currents resulting from post-dip reacceleration of such drives. Ideally a plant stability study should be made to establish that the plant will recover from severe dips. Retrofitting dip proofing should only be undertaken when it has been established that the drives can withstand the possible high level currents and torques; and the post-dip voltage depressions that could result.

5. REFERENCES

Ref 1 Dip-proofing of Industrial Plant - by R R Slatem (Technical Memorandum: issued by Escom March 1976) (Published in Transactions, SAIEE April 1976) (THIS ARTICLE INCLUDES AN EXTENSIVE LIST OF REFERENCES)

Ref 2 New Developments in M.V. Busbar Protection - by J J Wilson (Published in Vector, January 1992) Also associated letters to the Editor, published in Vector in March and May 1992, responding to the above article.