Evaluation of Protection Systems for Distributed Generation

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Background

Historically utilities have had to deal with customer generation on their radial distribution circuits only to a very limited extent. Many would simply not allow customers to operate generating equipment in parallel with their distribution facilities. With the passage of legislation such as PURA and an emphasis on utilizing renewable fuel resources and recycling waste, the interest in distribution generation began to rise. With a slow economy in the 1980's and early 1990's, there were not a significant number of customers taking advantage of these forms of power generation. With the up-turn of the economy and the 1992 Energy Act coupled with de-regulation on the horizon, the prospect of large amounts of generation on distribution circuits is becoming a very real possibility.

Operating Concerns

Operation of a generator(s) on a radial distribution circuits presents many more operating issues than the utility has dealt with previously. They cover a variety of areas including operation, protection, safety and others.

(A) Backfeed

A generator on radial circuit has the potential to backfeed the circuit should the substation feeder breaker open. With small generators (less than 1% of feeder capacity) this concern diminishes, but larger machines approaching 50% circuit capacity can easily maintain voltage and frequency on a circuit even when separated from the utility. Backfeed poses two potential problems. First, energizing the circuit during switching operations or maintenance can present a significant safety hazard to utility personnel as well as other customers and their equipment. Secondly, as an additional source during faults and disturbances it can cause additional protective relaying problems.

(B) Increased Fault Duty

With additional generation, the potential for lower system impedance increases the possibility for overrating both utility and customer equipment. Most customer generation is relatively small and individual unit contribution to faults is low. Potential problems can arise if multiple generators at a single customer or several customers with generation are on a single circuit.

(C) Harmonic Distortion.

Most rotating synchronous and induction generator machines in general do not produce objectionable harmonics. There is, however, a new generation of equipment becoming available that utilizes solid state inverters and other similar equipment to couple to the utility system. These devices have the potential to produce harmonic distortion high enough to cause problems with both customer and utility equipment.

(D) Islanding

The feeder can become isolated from the utility with voltage and frequency controlled by the isolated generator(s). With the inherent low inertia and capacity relative to feeder loading, excessive voltage and frequency swings could subject adjacent customers and utility equipment to over/under voltages and over/under frequency conditions, causing over excitation to motors and transformers.

Past Solutions and Reactions

Most customers' generator(s) contribution to feeder faults is small in comparison to system impedance. This makes detecting faults from the generator location difficult. Initially, utilities relied on their power plant experience in order to detect faults and trip the generator when necessary. They required customers to install a plethora of protective equipment without necessarily evaluating its effectiveness in a distribution environment. Many operating restrictions were placed on customers in order to ensure generator operation would not cause problems to the utility and other customers. Protective equipment was set overly sensitive to ensure tripping of the generator, but many cases resulted in many nuisance trips of the generator.

Protection Criteria

Fig. 1 illustrates a typical distribution feeder with a customer with generation. It is recommended that the customer provide some type of visible break disconnecting means at 'C1' or 'G1' so that both the utility and customer can ensure positive isolation of the generator from the utility supply. The important criteria from both the customer's and utility's standpoint is to ensure that for all operating conditions, if Feeder Breaker F1 opens, that the customer's breaker C1 or G1 opens to disconnect the generator. It may be desirable, however, for the customer to be able to isolate his facilities from the utility and operate all or a portion of his equipment independently. Some customers employ an underfrequency load shedding scheme and wish to isolate themselves from the utility should a feeder lockout occur.

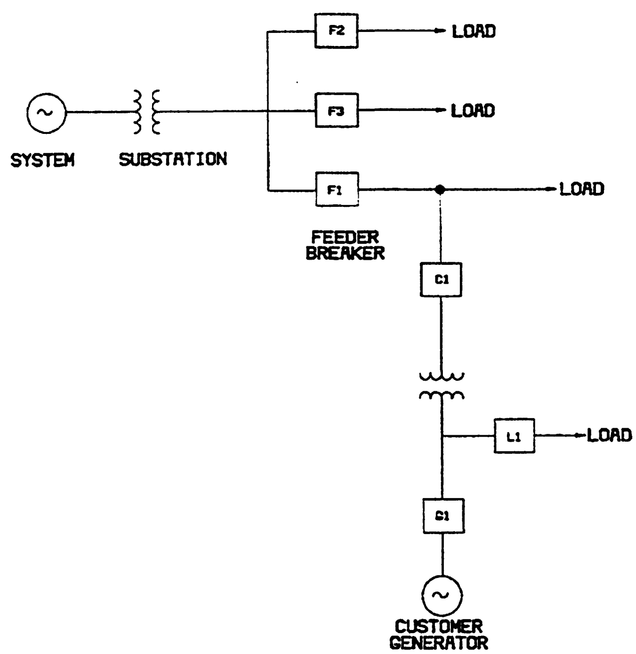
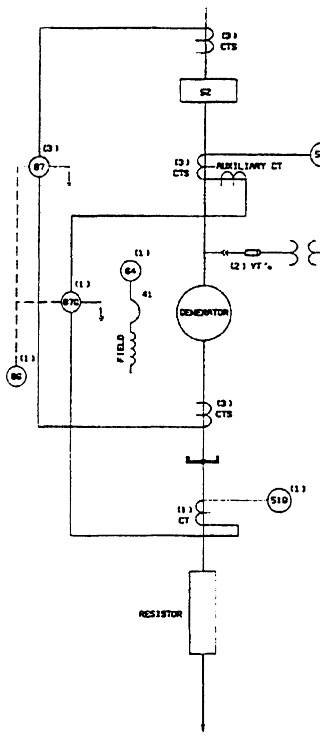


Figure 1

During transients such as faults, switching, etc., it is important that, when breaker F1 trips, either the customer's generator breaker G1 or breaker C1 must also trip. The customer's protective equipment must be capable of detecting the abnormal condition on the utility feeder. In general, over/under voltage and over/under frequency relays are sufficient to detect faults on the utility feeder. A typical generator protection scheme would include these devices as well as others; loss of field, voltage restrained overcurrent, and differential protection for the generator. Fig. 2 and 3 illustrate a typical protection scheme, for both synchronous and induction type machines. While the typical generator protection package will do an acceptable job of protecting the machine, it would not necessarily be optimized for detecting problems on the utility system and taking the appropriate action. Settings and relays appropriate for machine protection would not necessarily detect all disturbances on the distribution system. Conversely, setting these relays to attempt to detect remote faults and transients would result in unnecessary nuisance tripping of the generator. An overly sensitive undervoltage relay with little or no time delay would be an example. An additional problem is fault location. It is difficult to determine fault location whether on the customers or an



LEGEND

51V - VOLTAGE RESTRAINED OVERCURRENT
32 - REVERSE POWER
40 - LOSS OF FIELD
46 - REVERSE PHASE
64 - FIELD GROUND
86 - LOCKOUT
87 - DIFFERENTIAL
51G - GROUND OVERCURRENT (STATOR)

Figure 2

LEGEND

27 - UNDERVOLTAGE RELAY
27/59 - VOLTAGE RELAY UNDER/OVER
37 - UNDER CURRENT RELAY
47 - PHASE BALANCE/ SEQUENCE RELAY
51 - OVERCURRENT RELAY
59 - OVERVOLTAGE RELAY
51M - MOTOR OVERLOAD RELAY
81O/U - OVER/UNDER FREQUENCY RELAY
AM - AMMETER
C - CONTACTOR
FM - FREQUENCY METER
VM - VOLTMETER

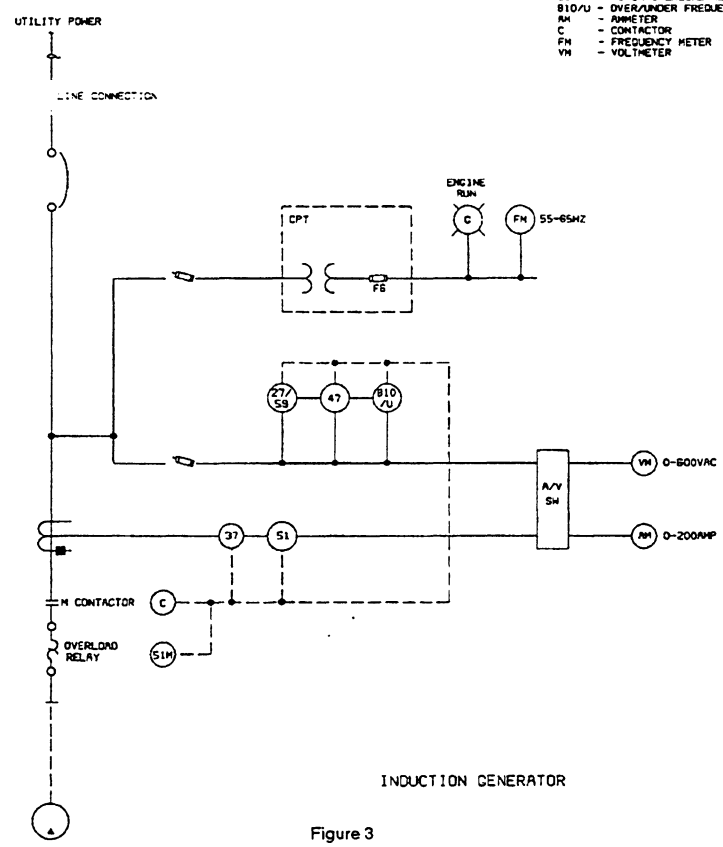


Figure 3

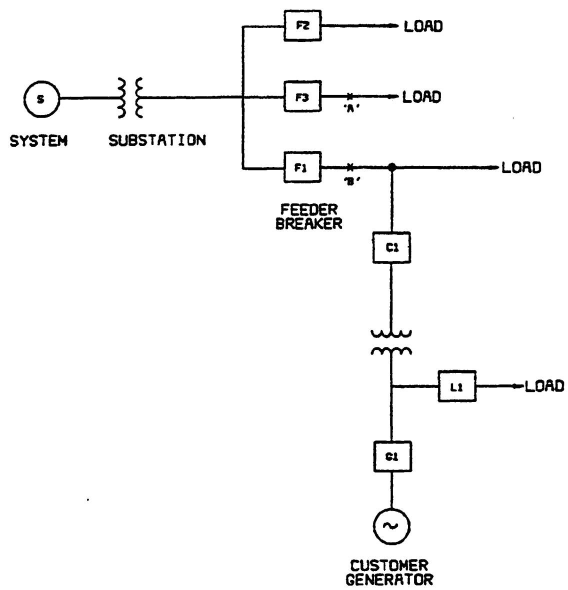
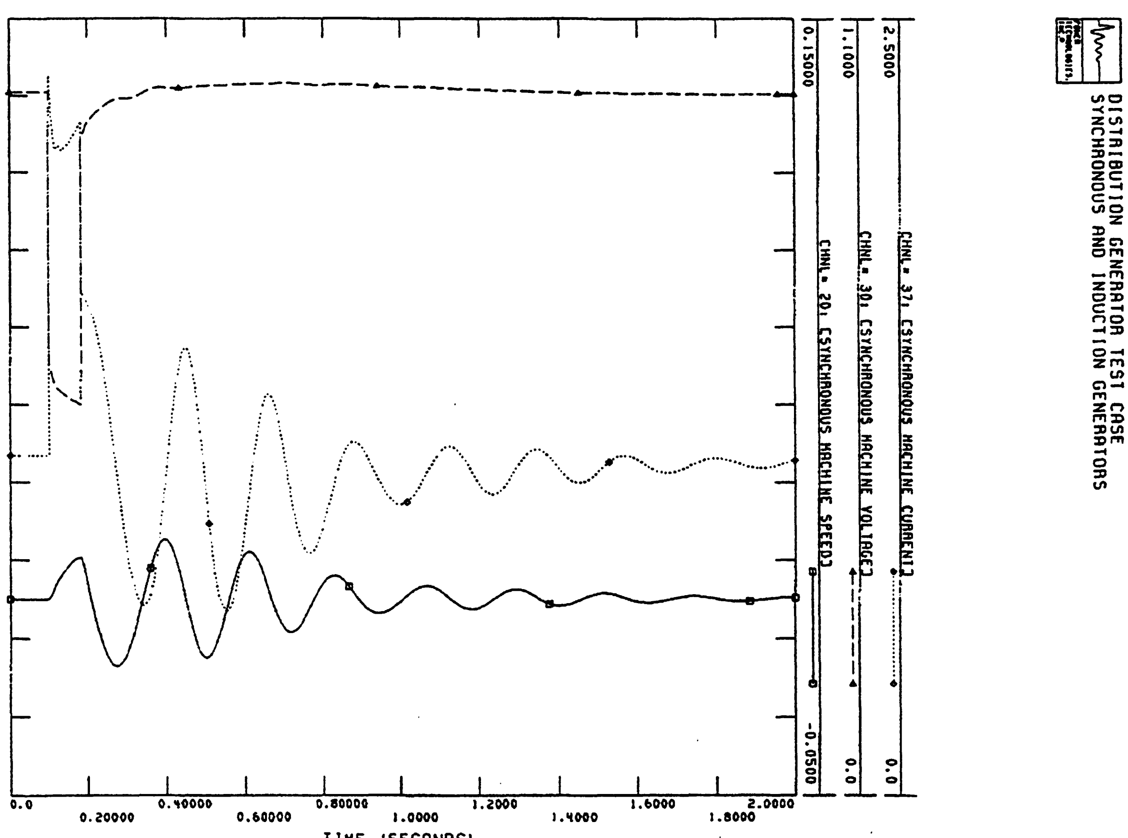
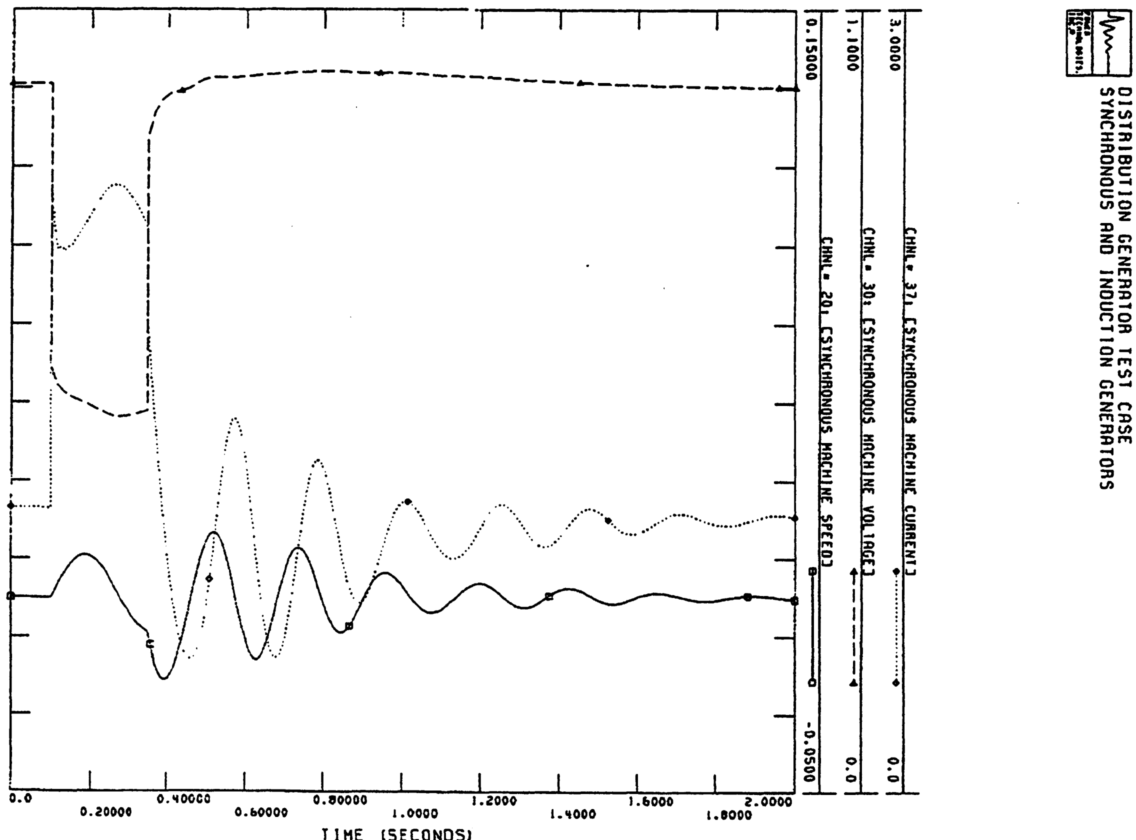


Figure 4



5 CYCLE BUS FAULT AT A

Figure 5



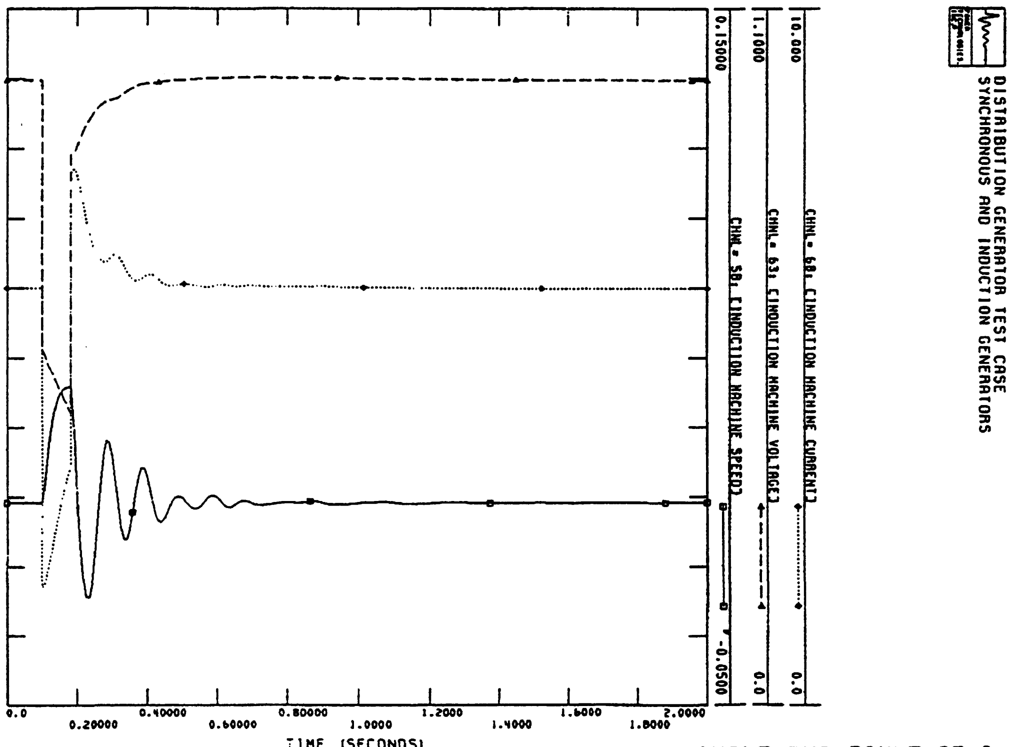
15 CYCLE BUS FAULT AT A

Figure 6

adjacent feeder from the generator location. For example, a Fault "A" or "B" in Fig. 4 would both be detected by undervoltage (27) relays at the generator but determining fault location (A or B) would not be possible. Figures 5 and 6 illustrate the voltage profile and machine angle swing at the customer's bus with a 4MW turbine generator for faults at locations "A" and "B". The feeder capacity is approx. 13mva with a load of 8mw. Given variations due to arc resistance, fault locations, etc., it is not possible to reliably differentiate faults at the two locations. Detecting faults reliably from the generator location results in tripping the generator in either case. Faults at location "B" require the tripping of the machine, a fault at "A" should be cleared by breaker F3. Fig. 5 illustrates a synchronous machine with a 5 cycle fault at "A', while keeping the generator connected to the utility, the stability of the unit is maintained and the generator remains connected to the system. Figure 6 illustrates a 15 cycle fault at "A" showing a synchronous generator voltage and machine angle swing while again keeping the machine connected to the system.. This tends to indicate that as long as system synchronizing power is available, the generator can withstand a significant disturbances and remain stable. A potential solution would be to introduce the delay in the undervoltage relay to allow breaker 'F3' to clear faults at 'A'.

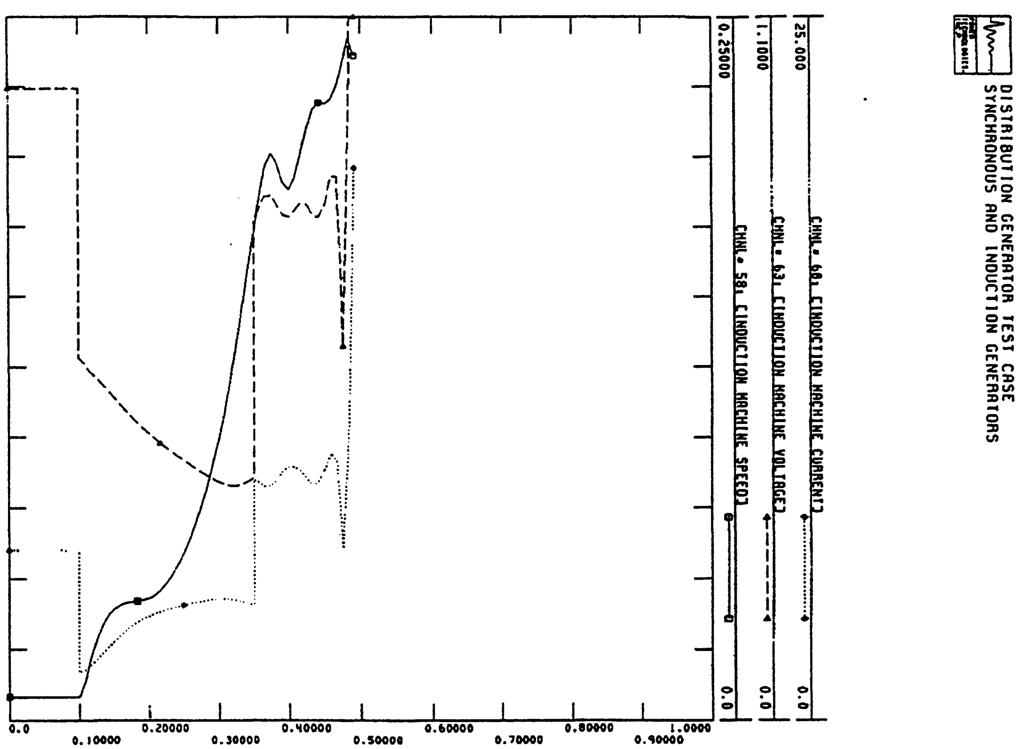
Similar studies were conducted using an induction generator as the customer generator. Fig. 7 illustrates an induction machine voltage swing for a 5 cycle fault at "A". Note the increased swing angle and swing frequency characteristic of an induction machine. Fig. 8 illustrates a 15 cycle fault at "A" and loss of machine stability. The induction generator machines generally cannot withstand prolonged voltage disturbance duration, and do not have as long of a critical fault clearing time as synchronous machines. This is due to much shorter winding time constants and lack of forced excitation.

In general, an undervoltage relay set to 70-75% pickup and an over/under frequency relay set to trip at 1% tolerance would be sufficient to trip the generator for all faults on the generator circuit as well as those on



5 CYCLE BUS FAULT AT A

Figure 7



15 CYCLE BUS FAULT AT A

Figure 8

adjacent busses. These settings would be sufficient to minimize nuisance tripping of the generator in cases where no time delay is used. Particular care should be used in installations involving ungrounded transformer connections to the utility. Ungrounded Wye and Delta connections can result in high voltages on customer equipment during ground faults. Separate ground detection scheme may be required in some installations.

Also of concern is isolating the generator with the distribution circuit not connected to the utility system when no fault occurs. With small generators, (less than 1 percent of circuit capacity), their ability to maintain circuit voltage and frequency is not as great, making this condition less difficult to detect. Note that in some extreme conditions with long laterals, it would be possible for a small machine to energize significant portions of a distribution circuit in an isolated radial condition. With large machines, those approaching 30% circuit capacity, the ability to maintain voltage and frequency becomes much more probable. Fig. 9 illustrates generator response upon opening of breaker 'F1' with a circuit loading of 8 MW. The generator is a 4 MW gas turbine synchronous machine. In comparison, Fig. 10 illustrates the same machine with a 5 MW load. This shows a much slower decay in frequency. The voltage drops and recovers in much less time as the voltage regulator/exciter recovers to maintain field voltage. Machine speed will drop as load/frequency equalizes. Time constants for this sort of step load change can be on the order of several seconds. For severe load/generation mismatches turbine under/over speed or under/over frequency relays will usually trip the generator.

It is possible though that load and generation could be close to being equal at the time breaker "F1" opens, resulting in little or no change in circuit flow or voltage. In the case of the induction machine, voltage will drop quickly upon opening "F1" and is reduced to 10-20% within the first few cycles. This response is illustrated in Fig. 11. Note that ferroresonant conditions are possible and circuit voltage may react unpredictably particularly if the generator is isolated with capacitor banks either at the customer location or elsewhere on the circuit.

Protection Schemes

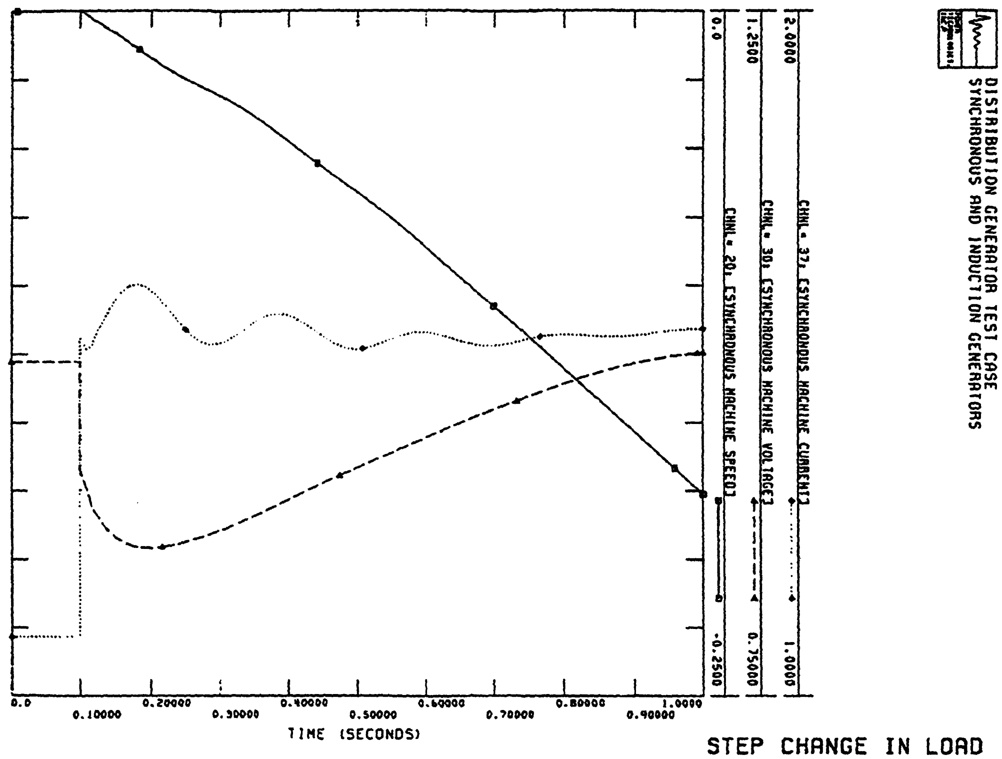
As seen from the examples, voltage and frequency deviation can be used to detect most abnormal circuit conditions to trip the generator, and these relays are highly recommended at the customer's location. It is possible, to use time delay with synchronous generators to reduce nuisance tripping for faults on adjacent feeders. This method should be used with caution as unit stability problems may occur for some machines with long time delays.

While voltage and frequency are good indicators of circuit condition, they cannot always be counted on to detect situations in which the customer's generator must be tripped. An example would be the inadvertent trip of breaker "F1", voltage and frequency at the customer's location may or may not deviate sufficiently to indicate a problem. Transfer trip from the utility to the customer is a positive method of tripping the customer's generation under such conditions. A simple scheme utilizing a single channel of communications to indicate utility breaker status is all that is required, but a more complex scheme providing more flexibility could certainly be used. Given its desirable characteristics as well as relatively low cost, transfer trip is highly recommended in customer generation installations. Additionally, the IEEE has additional recommendations that may be used in specific installations and configurations. These include impeadence relays, phase imbalance relays, reverse power, voltage-restrained overcurrent, etc. Each individual installation will have to be evaluated.

An important consideration that must be reiterated is how the customer generation is connected to the utility. While many customers connect their generation directly at utility primary voltage, various transformer-connected generators are also used. Abnormal conditions can result on the distribution circuit for ungrounded primary transformer connections. High transient voltage can result should the generator become isolated on the feeder through an ungrounded transformer. Different over/under voltage detection methods and ground detection schemes must be used for each type of interconnect. Again, none of these methods can positively detect all abnormal conditions from the customer location, making the use of some form of communication of feeder breaker status from the utility to the customer highly desirable.

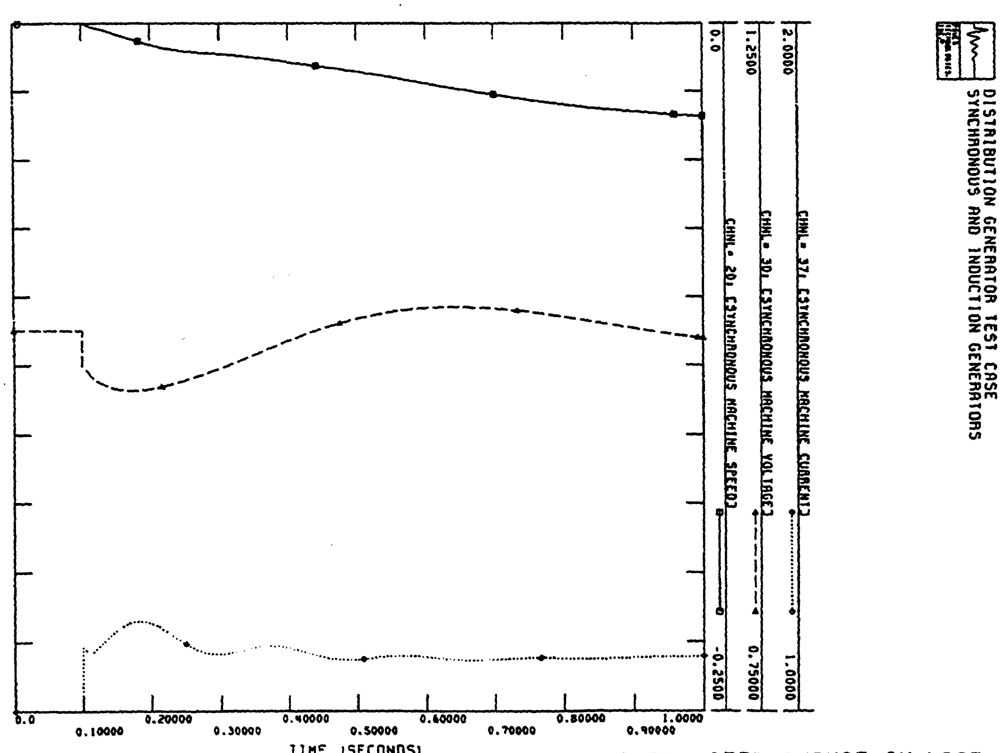
Reclosing

Of more concern to the customer than the utility is high speed automatic reclosing of the distribution



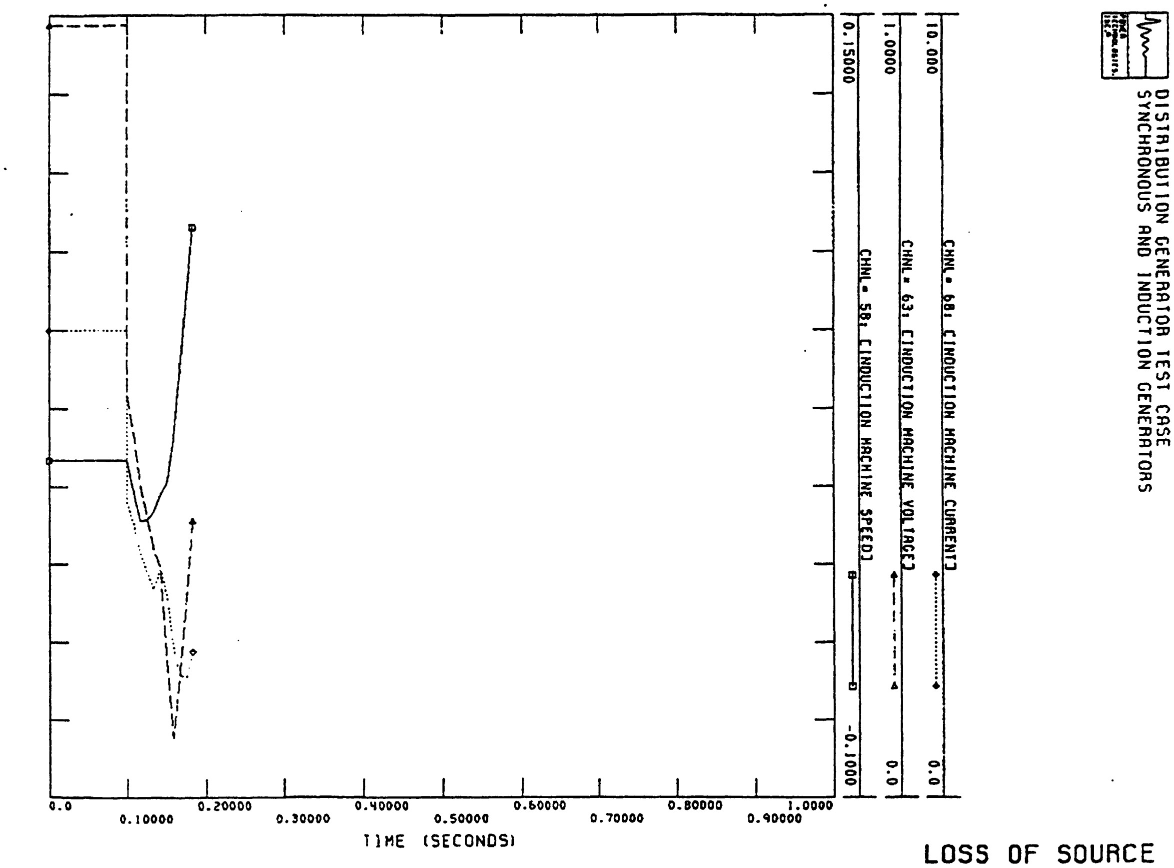
STEP CHANGE IN LOAD

Figure 9



SMALL STEP CHANGE IN LOAD

Figure 10



LOSS OF SOURCE

Figure 11

feeder circuit. Many utilities today use instantaneous reclosing for power quality reasons. If the customer's generator is still connected to the utility circuit, this can result in an out-of-sync reclosure, causing serious damage to the customer's generator. Reclose times on the order of 15-20 cycles are not uncommon. These short reclose times allow little if any margin for the customer to detect the condition and disconnect his generation equipment from the circuit. Using under voltage/frequency, impeadence relays, etc., to detect disturbances necessitates a sensitive relay setting, resulting in unnecessary tripping of the generator for remote faults. Transfer trip is a positive means to insure a timely trip of the generator when the feeder breaker opens, and yet prevent nuisance tripping for fault on adjacent circuits.

Conclusions

We have discussed several aspects regarding generation on radial distribution circuits. I would like to highlight several important conclusions:

I. Small generators (less than 1% of circuit capacity) are generally not capable of backfeeding the distribution circuit during a fault or disturbance. It is possible to use only minimal relaying to detect such events and disconnect the machine.

II. Conventional generator protective relaying may not be sufficient to detect all utility system disturbances and properly disconnect the generator.

III. The utility must ensure the customer has installed sufficient protective equipment and proper settings to detect faults and disconnect the generator for all cases.

IV. In some cases, it is not possible to detect a utility feeder breaker operation from the customer location. A transfer trip scheme is highly recommended to ensure that the customer's generator is disconnected should the utility feeder breaker open.

V. The method of interconnecting the generator to the utility must be taken into account. Ungrounded transformer connections can result in severe over voltages should the generator and distribution feeder become isolated from the utility.

VI. The utility reclosing practices must be accounted for to prevent reclosing into the customer's generation out of sync. This is particularly true when instantaneous reclosing (less than 1 second) is used. Again, transfer trip provides positive indication of the feeder breaker status to the generating equipment.