Connection of a Distributed Resource to 2-Transformer Spot Network

M. Baier, *Senior Member IEEE*, W. E. Feero, *Fellow IEEE*, and D. R. Smith, *Fellow IEEE*

***Abstract*--Recent energy crisis brought about renewed interest in connecting distributed resources (DR) in spot networks of downtown metropolitan areas. Several important safety and technical constraints exist that need to be addressed by the developer and the utility. While interconnecting DR to the utility is often a complex issue, interconnecting to secondary networks is always complex and not always possible.**

This article highlights an approach taken for successful installation of a 75kW DR to a spot network supplying an office building. In the subject case an indiscriminate connection of DR would have resulted in serious consequences to system integrity. The solution consisted of applying power relays for automatic supervision of the DR depending on the conditions in the system. The signals were derived directly from the network protectors ensuring full integrity of the system. Tests demonstrated that the installation performed as designed. DR is now in operation for one full year.

***Index Terms*--Generator, distributed generation, distributed resource, secondary network, spot network, network protector, network transformer, overpower, underpower.**

I. INTRODUCTION

The growth of electricity consumption and our dependence on this form of energy in the United States brought about some widely publicized concerns of power shortages in the last decade. These concerns were deepened in some areas by the power industry deregulation. Proliferation of distributed generation was a natural reaction of the consumers to the availability of power reflected by its price. Downtown areas are becoming prime candidates for the distributed generation, as these areas are growth-constrained. It is in these downtown areas where secondary networks are a very common type of power distribution system.

The types of distributed resources (DR) that are typically found in the municipal setting may range from the more conventional reciprocal engine-powered sources fueled by diesel or natural gas, to more modern types such as micro turbines, PV and fuel cells. Smaller units typically employ induction type generators while larger units (from hundreds of kW to megawatt outputs) use synchronous generators. The generators are commonly directly coupled to the power system although the use of low-harmonic, solid state inverters is becoming very common for newer types of DR.

Secondary networks were designed to accommodate the requirement for higher reliability and better voltage regulation in high load density areas in downtown metropolitan areas in North America. Since its inception in the twenties, this type of distribution has seen steady growth.

The networks are multiple feeder systems meshed together through network transformers so that every low voltage secondary node (bus) is supplied from at least two sources. The most common network voltages are 120/208V and 277/480V. Because these systems provide service to individual customers, the networks are commonly solidly grounded at the network transformers. Individual network branches are switched by a special circuit breaker called a network protector (NWP). The network protector is typically housed in a watertight enclosure attached to the low voltage side of the network transformer and situated in the vault under the street or in the basement of a building.

The network protector is designed with a very sensitive and fast reverse power protection with the objective to isolate the network in the event of the outage or fault on the primary feeder. The tripping time of the NWP is as short as a few cycles (50ms). Once the fault on the primary of the network transformer is cleared, the protector automatically recloses when the voltage at the network transformer is restored to its required level. Normal loads that are connected to the secondary bus do not produce sustained currents in the tripping direction of the NWP, but generation connected to the secondary bus may.

It is this rapid tripping from back-fed currents that poses the concern of system integrity when the distributed resources are connected to the spot network. The consequences of islanding and the inability of the networks to self restore their operation under these conditions are the principal reasons for the reluctance to accept distributed generation in secondary networks. As an illustration of the sensitivity of the network protector reverse tripping capability, several instances have been reported when, during light load conditions in the spot network-supplied high-rise building, elevators tripped protectors during their braking regime.

Under light load condition, quite conceivable for larger DR, an entire spot network can become an island. This is a condition that is totally unacceptable with one of the following consequences:

- *Catastrophic failure of the NWP*: Most in-service units are not rated for the separation of two independent, non-synchronous systems. Island gets reconnected by a NWP auto reclosing master and phasing relays, creating hazardous condition. The NWP relays are not designed nor tested to function in non-synchronous systems.

- *Safety Hazard:* Losing control of the supply voltage and exposing the public to a potential life safety situation is a violation of a regulated utility charter.
- *Outage:* If DR itself doesn't sustain normal operation (induction generators, inverters) outage results.
- *Equipment Damage:* DR on an island results in hazardous condition, such as self excitation, and customer's equipment can be severely damaged.

This article demonstrates that in certain system configurations, islanding can be prevented so that these very real concerns will not materialize. However, even with the prevention of islanding, there are other issues that must be addressed such as NWP cycling and maintaining true network quality service. One such solution was implemented by the authors of this article and is described herewith. Finally, several important conclusions are drawn and guidelines are provided to determine whether an installation qualifies as the DR site. These principles are illustrated on the example of a 2-transformer spot network for transparency. However, most of the conclusions and guidelines derived herewith are believed to be generally applicable also to spot networks containing three or more transformers.

II. Challenge of Operating DR on Spot Networks

Many utilities are reluctant to accept indiscriminate deployment of distributed resources in secondary network systems because of the concern of DR jeopardizing life safety, system integrity, and power quality. This is especially true for spot networks lacking load diversity where during the minimum load condition, one or more network protectors could trip on reverse power flow out of the network. Furthermore, under certain circumstances or when the distributed resource is of a type that could sustain fault current, it could trip one or more network protectors. This is why additional measures may be necessary to safeguard the installation when distributed resources are operated on the spot networks.

This article discusses an approach of safeguarding the spot network by detecting the above conditions and disallowing the operation of the DR before the network protectors open. A minor trade-off is necessary under low current backfeed conditions, as the network protector trip has to be delayed by a fraction of a second to allow removal of the local DR from the system. This minor modification of the NWP tripping characteristic only takes effect for the low current magnitudes so that the power quality is not compromised during system faults.

The concept relies on supervising the power supplied from each protector to the spot network with a three-phase under power relay. True three-phase power elements with instantaneous trip contacts are employed. Even in multi-transformer spot networks, individual monitoring of each network protector (as opposed to using a total power summation scheme) may be justified due to unequal load sharing between the transformers.

The underpower element (ANSI Device Number 37) senses an instantaneous power flow to the spot network through the network protectors and trips the DR unit when such power flow drops below the minimum permissible threshold. Once tripped, DR is not allowed to reconnect to the system until a time delay, typically five minutes, has elapsed, during which time certain minimum number of NWPs need to be closed and their real load remaining above the maximum power threshold. The resetting of the circuit logic following the stabilization of the load above the maximum power threshold is controlled by a separate power element. The time delay is adjustable from 1 to 300 second.

In assessing the feasibility of a given installation, the load profile of the facility has to be well known. It is often tempting to use a power billing information available from the accounting department or the utility. This may be an entirely acceptable practice in the installations where the size of the connected DR is only a small fraction of the minimum load of the facility. In a more general case, or when the DR size approaches or exceeds the minimum load of the spot network, more cautious approach is advised. Specifically, distinction should be made between the type of data available from the energy meters and the specialized power analyzers. As the demand readings are typically based on fixed interval (commonly 15 or 30 minute) averages, they tend to mask intermittent power fluctuations and swings. Such power swings can be often caused by starting of large rotating loads or, more importantly, by the regenerative swings (braking) of the elevators.

Load study is also necessary to arrive at the suitable power settings, once the installation is deemed feasible. The minimum power threshold is estimated from the measurement of the minimum system load and any experience that has demonstrated minimum load without protector cycling. This estimate should take into account the fact that the network protectors may not share the load equally.

Starting at the instance of low magnitude reverse current in a network protector which might be caused by the presence of the DR, the network protector tripping has to be delayed slightly using a special delayed tripping function available with modern network protector microprocessor-based relays. Emphasis should be given to delaying the protector trip only for the low current magnitudes while preserving the instantaneous trip function for the higher currents (faults). This function is similar to the time-current characteristic of the combination of an instantaneous and a time-delay overcurrent element (50/51) frequently used for the coordinated protection of radial distribution feeders.

The application also needs to be scrutinized for the scenario of the fault on the primary side of a network transformer. This is illustrated on an example of a 2-transformer spot network by Fig. 1 and Fig. 2 respectively. For the purpose of illustration resistances and conductor impedances were neglected. Approximate fault current contributions for a bolted three-phase fault at the primary of the network transformer are calculated using a current superposition method. Base quantities of 480V and 1202A (1MVA) were used for the calculations. The results are presented in per unit notation and rounded.

Fig. 1 illustrates the effect of fault current contributions in the system with the primary substation tie open. It is noted that, in the protector adjacent to the one associated with the faulted feeder, the fault current contribution from the utility tends to overcome the generator contribution and the protector remains closed. In the protector associated with the faulted feeder, on the other hand, both system and DR contributions act in the same direction. The resulting flow into the transformer is much higher than that of a generator contribution alone and the protector trips instantly. The relative magnitudes of both fault contributions could be of significant importance especially when desensitizing feature is used in the network protector relays.

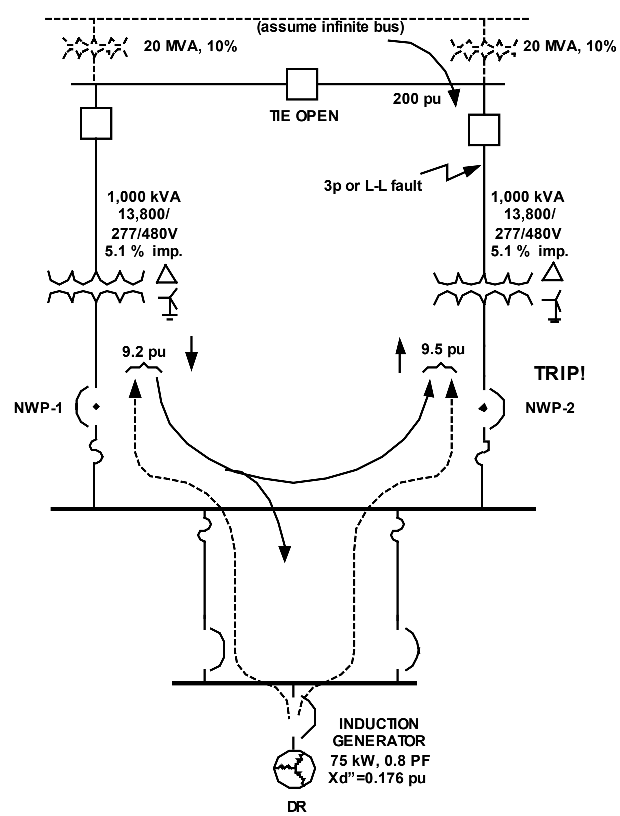

Fig. 1. Fault currents for primary fault, tie open

Fig. 2 shows the system with the primary tie closed, the preferred feeder configuration for supplying secondary networks. When the bolted three-phase fault occurs in the electrical vicinity of the primary distribution bus, the system contribution through the network transformers diminishes to the point that both network protectors sense the similar reverse flow. The generator is effectively the only source of the fault current from the network. Because this fault current contribution is much less than with the system contributing, it is possible to delay the tripping for a fraction of a second without exceeding the feeder fault rating. After the feeder breaker has cleared the fault, the low magnitude fault current from the DR will be overwhelmed by a large fault current contribution from the utility back feeding the fault and the NWP will trip instantaneously. Only if the fault current stays low, as in the case of a high impedance fault, will the NWP not trip until the full time delay. Under this circumstance if the instantaneous trip point is set low enough, there will be no compromising of the power quality in the network.

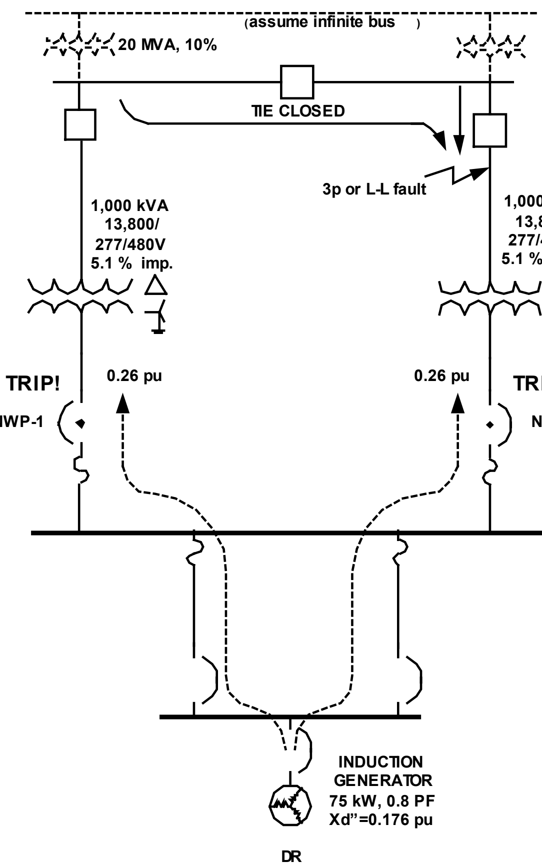

Fig. 2. Fault currents for primary fault, tie closed

Fig. 3 uses a semi-logarithmic graph of current decrement of both components of the short circuit current to illustrate the time-current coordination of the NWP trip under the reverse power flow condition.

During light load condition, one protector may open and remain open while the other protector is carrying the load. This condition is commonly referred to as "float" condition. This property brings another interesting problem to our discussion. Let us consider a configuration with tie open depicted by Fig. 1. Assuming that the fault on the primary feeder is associated with the closed protector, it is easy to follow that unless the protector tripping is delayed, islanding may results as a direct consequence of adding DR to the network.

Even without a split bus feed that can cause power flows which open one of the protectors, maintenance procedures or circulating currents under very light load conditions can cause one of the protectors to open. When this occurs, which ever is the cause, the NWP master and phasing relays are designed to wait for a preset voltage magnitude and angle difference across the protector before they permit its reclosing. This feature is intended to ensure that power will continue to flow into the network after the protector closing, therefore preventing its cycling. Because of this feature, the presence of a DR could significantly delay or prevent the reclosing of the second protector, as DR is effectively reducing the load on the in-service network protector(s). Such delays would not only increase the chances of islanding, but also directly effect the time that the network is exposed to a feeder fault which could result in a network outage.

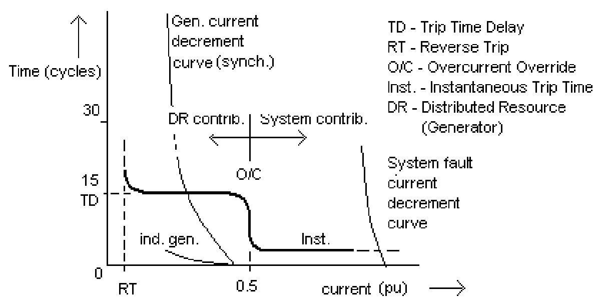

Fig. 3. Time-Current Coordination of NWP Trip

In the following section, protective settings will be discussed with regard to the minimum coordination of the DR/Network interface protection with the network protectors. First, an overpower trip setting, P_0, should be determined. This is the power flow that must be realized in each closed protector following generator tripping from an underpower condition, before the generator is allowed to reconnect. It is based on the minimum number of network protectors supplying a multi-transformer spot network for which DR is to be allowed to remain on line, as follows:

$$P_0 = 1.2(P_G /n + P_U + \Delta P)^{1} \qquad (1)$$

where

- P_U desired under power setting per protector (DR trip power level) while positive and preferably below the minimum measured instantaneous network load;
- P_G rated generator output (aggregate from all sources);
- n number of transformers or NWPs supplying the spot network;
- ΔP safety margin reflecting the network load fluctuation.

An arbitrary multiplier of 1.2 is used here as a design safety margin. This multiplier may reflect unequal load sharing between transformers in the spot network if the load summation scheme is employed.

There should be no intentional delay introduced in the tripping of the DR when an underpower condition occurs. This allows the closest coordination of the DR tripping time with the tripping characteristic of the network protectors. The minimum tripping delay of the network protectors equipped with microprocessor relays, for example, is 0.25s. A total DR tripping delay of 125ms gives a protective margin of another 125ms, which is acceptable for the coordination between two calibrated solid state protective devices.

Selection of the overpower setting needs to reflect the actual load profile in the facility. If it is too low, excessive cycling of the DR may result. Too high a setting, on the other hand, may unduly restrict the operation of DR thus reducing the expected revenues. Closer settings may be allowed if the DR has a capability to regulate its power output as a function of the load in the facility.

As stated earlier, the reverse tripping of all network protectors in the spot network should be delayed only by a minimum time to allow disconnection of DR during specific system conditions that could cause the spot network to become an island. Further, the overcurrent setting of the time delay function only needs to be set above the subtransient contribution from all downstream sources. This way the network protector trip is delayed only for the current magnitudes from the distributed resource and not for the contribution from a primary source that would prevail for faults on supply feeders as shown earlier.

Network protectors are designed and tested to trip on the primary faults of very high magnitudes when the network voltages are severely depressed. The DR/Network protection needs to function at these low voltages, and should exhibit reliable tripping at low power factor, typically 0.15 lagging.

III. Case Study

A utility in the East was approached by their customer who planned to connect a 75kW induction generator to the 480V spot network supplying their facility. The 277/480V four-wire building network is supplied by two network protectors rated 1875A equipped with microprocessor relays. The protectors are throat-connected to the two 1000kVA network transformers in the vault. The NWP manufacturer and an independent consultant were approached by the utility to propose a solution that would allow connection of the said generator without jeopardizing the life safety and reliability of the power system. This section discusses the proposed solution. The existing system prior to modification is shown in Fig. 4.

The utility was concerned that during the minimum load condition in the network while the DR were running, one or both network protectors could trip on reverse power flow out of the network. Another concern was the potential of the protectors' trip during the faults upstream of the network protectors. The load of the building consists of lighting,

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[1] select next higher available setting

computer loads, air handling equipment and elevators. One-week long monitoring of the load supplied by each network protector was conducted to capture the load profile and the instantaneous load swings not apparent from the demand analysis. A dedicated 3-phase power analyzer was set up to monitor the power with one cycle resolution. The results of load survey revealed that the total building load reached 500kW during a hot spring day, while the minimum system load was about 120kW.

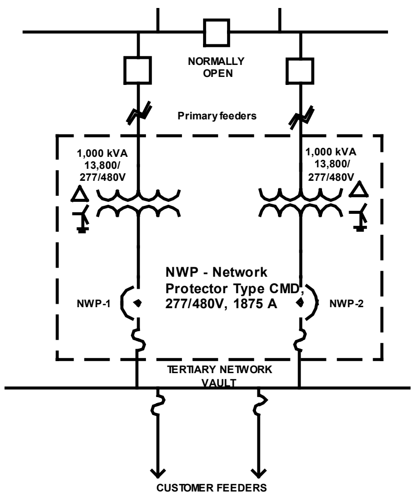

Fig. 4. Existing Distribution System

To maintain status quo of the protector system until operating experience with this system could be developed, each underpower relay has been conservatively set to trip the DR upon reaching the underpower threshold of 59.6 primary kW in each protector. The reset power level (overpower setting) was set at 132.5 primary kW per protector. It is anticipated that once the operating experience with this system is gained, these settings can be reduced to as low as 30kW for the under power unit and 88kW for the over power unit.

The delayed tripping function of the type MPCV microprocessor relay is known as the BN function. It introduces the trip delay adjustable between 0 and 300 seconds in 0.25s increments for currents within an overcurrent (O/C) threshold adjustable between 1% and 250% of the NWP current transformer rating. Above the O/C setting the protector reverts to instantaneous tripping. For this installation the O/C was set at 50%.

To accommodate the additional protection, a separate protection panel was placed outside of the protectors in the vault. The current and potential circuits were brought out from each protector using conduits and special watertight hardware. The schematic representation of additional circuits is in Fig. 5. The new and retrofitted equipment is shown in dashed lines.

Fig. 6 shows the control circuit used to supervise the DR operation based on the load conditions in the network and the status of the network protectors where

NWP is network protector type CMD, 277/480V, 1875A (1600A CT rating) , retrofitted with MPCV relay;
37 Under/Over power relay BE1-32 O/U;
62 timer 120 V, 0-300s;
86 lockout relay with manual reset;
94 trip relay with electrical reset;
CPT control power transformer 480/120V;
PSS power supply status contacts of device *37*;
DR distributed resource (generator);
TCM trip circuit monitor relay.

The protection panel houses two dual-element three-phase power relays (device 37), the control power transformer, and other auxiliary control devices. Status indicating lights and an emergency trip push button were placed on the outside of the enclosure door. The front view of an open cabinet is in Fig. 7.

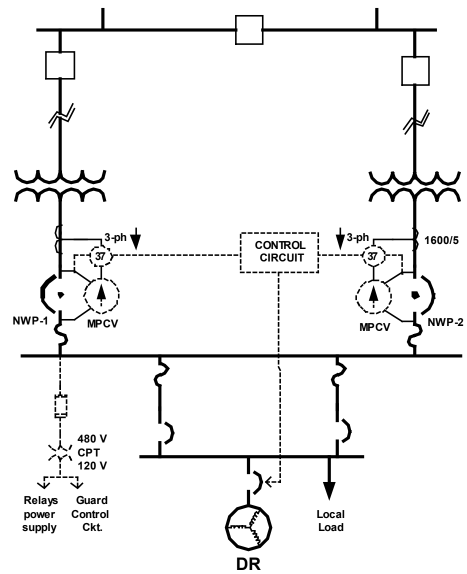

Fig. 5. Proposed Modifications

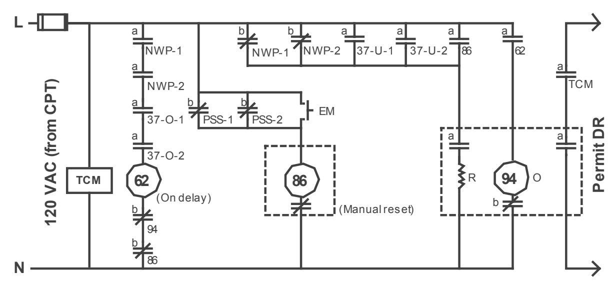

Fig. 6. Proposed Control Schematic of DR Control Circuit

The three-phase relays sense the real power in the normal direction (into the network) in each protector and instantaneously close their contacts when the power in either network protector decreases below an underpower setting. The trip contacts are wired in the control circuit of the generator. Once the generator trips, it cannot be reconnected for up to five minutes after the power of the facility returns and remains above the relays overpower settings. This feature is incorporated in order to prevent on/off cycling of the DR. This is illustrated in Fig. 8.

Several additional features were incorporated in the design to further safeguard the system from islanding:

- *DR Trip (operation suspended):* When one or both NWPs open or control power is lost – indicated by an amber light "Trip" (this condition is subject to auto reset).
- *DR allowed to operate:* Indicated by a white light "Ready".
- *DR emergency trip:* Loss of relay power or blown control fuse – indicated by an amber light "Locked Out" (this condition is subject to manual reset).

Fig. 7. Front View of Open Protection Cabinet

During startup, a series of tests were performed on site to commission the system. The main purpose of the tests was to ascertain that the selected protective/control scheme would provide the required protection in the abnormal system conditions. Such conditions include, but are not necessarily limited to, the conditions that could cause one or both network protectors to trip on reverse power flow contributed to by the generator.

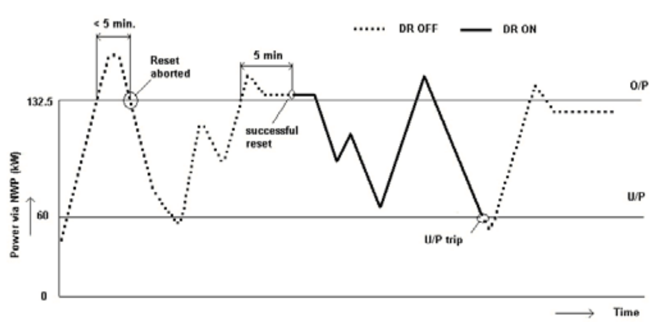

Fig. 8. System Deadband Operation

IV. OBSERVATIONS

The case discussed allows certain conclusions and general projections. From an application standpoint, some minimum system requirements should be observed, based on the concept of preventing network disruption by disallowing DR operation during power export out of the network or during primary fault back feed. Several important recommendations can be made that could be formulated as minimum system criteria for the preliminary system qualification:

A. DR Size Limitation

Ideally the minimum, but certainly the average daily load supplied by the spot network should be above the maximum aggregate DR capacity. DR utilization and resulting revenues are reduced in direct proportion with the time during which the minimum load criterion is not met.

B. Load Characteristic

Billing demand analysis may not suffice when minimum system load nears the aggregate DR size. If this is the case, the load characteristic has to be studied in depth, which may require special instrumentation.

C. Delaying Of Network Protector Tripping

Any DR aggregate rating approaching the network minimum load must rely on delaying NWP trip at low current levels using discriminated delayed tripping concept. NWP owner (commonly utility) needs to approve ahead of time. Coordinated delaying of the network protector tripping is only possible by retrofitting all network protectors with modern microprocessor relays, the cost of which must be included in the DR's financial analysis.

D. Feasibility Study

If any of the above conditions are not met or are met only marginally, a feasibility study may be necessary which increases the cost of interconnection.

E. Testing

Commissioning tests are likely to become mandatory for any installation under the new IEEE standard P-1547 [1] expected this year. Under and over voltage and frequency settings at the DR protection will not be sufficient to prevent undesired protector tripping even under fault conditions. Suitable testing provision must be provided so that the protection can be tested during operation of the network. Finally, maintenance testing procedures and scheduling should be included in the financial analysis.

Standards:

[1] *Draft 10 IEEE P1547 Standard for Interconnection of distributed Resources with Electric Power Systems*, Aug. 2003.

Books:

[2] R. C. Dugan, M. F. McGranaghan, S. Santoso, H. W. Beaty, *Electric Power Systems Quality,* 2nd Edition, McGraw Hill, 2002, Section 9.6.

V. BIOGRAPHIES

Martin Baier (M'86) was born in Prague, Czechoslovakia, on September 26, 1949. He received his MSEE degree from the University of Prague in 1973.

His employment experience included the Czech Energy Enterprises (CEZ), Westinghouse Electric Corporation since 1985, and with Eaton Cutler-Hammer since 1998. His special fields of interest included Power Quality, Predictive Diagnostics and Distributed Generation. Mr. Baier co-authored several patents in the area of power system grounding and insulation diagnostics. He is currently a principal engineer of engineering services of Eaton Cutler-Hammer and an active participant in IEEE P1547 Standard development. He is registered professional engineer in Pennsylvania and Ontario, Canada.

David R. Smith (F'86) was born in Altoona, PA on January 1, 1942. He received the BSEE degree from the Pennsylvania State University in 1963, and the MSEE degree from the University of Pittsburgh in 1968.

He was employed with Westinghouse Electric Corporation from 1963 through 1988, working in areas related to power distribution system analysis, equipment application, and special studies. Since 1988 he has continued these activities for Power Technologies, Inc., currently being an Executive Consultant. His main areas of interest are the design, operation, and protection of low-voltage networks. He is co-holder of two patents on network protector relays. Mr. Smith is a registered professional engineer in Pennsylvania.

William E. Feero (F'88) was born in Old Town, ME in 1938. He has degrees from the University of Maine in 1960, University of Pittsburgh in 1969, and MIT in 1972. From 1960 to 1976 he was employed with Westinghouse Electric Corporation in the Advanced Systems Technology Division specializing in transient analysis and protective device coordination. In 1976 Mr. Feero was appointed the program manager of the Power Supply Integration Program of the Division of Electric Energy Systems of the Department of Energy. The program provided for the timely and orderly integration of new source technologies into electric power systems.

After taking early retirement in 2000 from Electric Research, a company he co-founded in 1980, Mr. Feero is currently a consulting engineer specializing in power delivery analysis and studies of interconnections with utility systems. A major research focus has been the characterization of the dynamics associated with interfaces between small power producers and existing electric utility systems. His career has been enhanced by serving on the PES T&D Committee, the PES PSRC, the SCC28, the SCC23, and the SCC21. He is a registered professional engineer in Pennsylvania and Maine.