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# Industrial Power System Automation: Synergistic Benefits Of Integrating Protection, Instrumentation And Control

An IEEE Technical Paper* Co-Authored By


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## ABSTRACT:

Advancements in microprocessor technology have resulted in greater performance at decreasing cost. This technology is being successfully applied to protection, instrumentation and control of industrial power systems. Integrating these functions through data communications results in a synergism, such that the collective benefits exceed those which are achievable individually. This paper explores the various ways in which industrial power users may benefit through reduced energy costs, more efficient utilization of power distribution equipment, and improved power system reliability. It is anticipated that creative users will use these examples as catalysts for discovering additional innovative applications.


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## INTRODUCTION

Smart houses, intelligent buildings, factories of the future, or power system automation. Potential applications of microprocessors to solve electrical power problems abound. Indeed, advancements in microprocessor technology have resulted in greater performance in terms of speed, data storage, and reliability — all achieved at decreasing cost.[1] Power distribution equipment manufacturers are taking advantage of this technology, incorporating powerful microprocessors in protective devices, metering products and control systems. However, the greatest benefits are to be realized by integrating these functions through data communications. The result is a lower overall system due to the inherent synergy involved. In addition, by sharing data with a central processor, the collective benefits exceed those which may be achieved on an individual basis. It is precisely this synergistic effect which marks the difference between an expensive set of "bells and whistles" and an integrated system which represents significant value to the power user.

Simple data communications capabilities have recently been introduced in a number of electrical products, typically through the use of an industry-standard serial port. Programmable controllers are also being applied in power equipment with great success, performing automatic control based on relayed signals from protective devices. By integrating these components through data communications, the programmable controller can serve effectively as a "system management unit". The preprogrammed "intelligence" to evaluate circuit data and make decisions is built-in, allowing the PC to perform sophisticated control and protective functions. Combining micro-based instrumentation with this system allows a PC (or another central processor) to perform information gathering, reporting, and storage functions. Creative users have found a number of interesting and significant applications to put these capabilities to good use. These benefits represent real savings in terms of reduced energy costs, more efficient utilization of power distribution equipment, and improvements in power system reliability. Microprocessor-based implementations of protection, instrumentation and control systems offer many user benefits individually; this paper will focus on those synergistic benefits made available when these functions are effectively integrated through data communications.

## SYNERGISTIC BENEFITS: INDUSTRY APPLICATIONS

The primary function of electrical power distribution equipment is to support safe, reliable supply of energy while providing equipment protection for the system itself and connected apparatus. Thus, the independence of overcurrent protective devices is normally considered a top priority to ensure reliability. Trade-offs in terms of centralized vs. distributed processing have traditionally favored separate overcurrent protection for each circuit. Control functions and some auxiliary protective functions, which by their nature involve a systems approach, are often accomplished centrally. By networking components through data communications, the desired independence of critical overcurrent protection can be retained without sacrificing the many additional benefits of system integration. Indeed, the overcurrent protection function itself can be enhanced through this approach. Additional user benefits may include preventive maintenance capabilities, improved system diagnostics, system planning assistance, automatic recordkeeping, automation of control functions, and increased system reliability. (Refer to Figure 1.)

### Advanced System Protection

Early microprocessor-based protective devices did little more than mimic the same features currently available through thermal, electromechanical or other means. By adopting a systems approach, microprocessor based protective devices may be utilized to accomplish advanced protection beyond that which may be obtained by conventional means. The basic, critical overcurrent functions may be left to perform independently at each device, but auxiliary protective functions can be made more intelligent by incorporating supervision from a central vantage point. For example, a centrally controlled system can adapt protection levels of these auxiliary functions to closely match the requirements of circuit conditions.

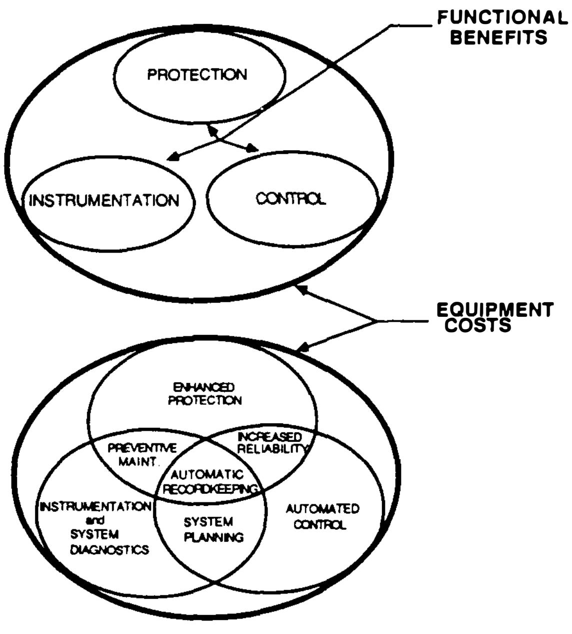


Fig. 1 Integration of protection, instrumentation and control functions results in increased benefits with little or no increase in equipment costs.

Typically, protective devices are set at a given protection level at start-up and then forgotten. Yet, a power system's loading and protection requirements are constantly changing. This dynamic nature often dictates that conventional devices be set at levels less sensitive than desired, simply to avoid unwanted interruptions ("nuisance tripping") that may occur during extraordinary periods of operation. By adopting a centralized, systems approach, protection levels can be adapted according to the dynamic requirements of the power system and its loads. Set points for the various protective functions can be automatically adjusted based on time constraints or external conditions.

Time of day, day of the week, or seasonal trends may influence system protection requirements. For example, a manufacturer's world headquarters office building is able to tolerate voltage flicker or other undervoltage conditions in the evenings or on weekends, but during normal business hours, such undervoltage conditions must be minimized. Thus, protection levels and associated corrective measures can be designed to achieve this end, while allowing sensitive voltage settings to be relaxed during off-peak times.

Seasonal variations in loading (for example, heating loads in winter and cooling loads in summer), may also dictate varying degrees of protection. Though fed from essentially the same supply, heating and cooling equipment may require differences in protection against variations in voltage, frequency, phase unbalance, etc. A solution to this problem is to automatically adjust protection levels based on the actual requirements at a given time.

Conditions external to the power system can also impact protection levels in a number of ways. Consider, for example, a specialized machine which requires very sensitive protection but operates only part of the time. With conventional systems, two choices are possible: selecting sensitive settings which result in over protection during the times when the special machine is not connected and introducing the possibility of nuisance tripping; alternatively, less sensitive settings may be selected, sacrificing the protection required when the specialized machine is connected. With an adaptive system, the sensitive set points could be utilized only when needed — when the special machine is on line.

Operator actions also influence protection levels and may require a greater degree of flexibility. An example of this involves a food producer whose maintenance crew will be performing work on various equipment installations. Anticipating that temporary undervoltage conditions may occur, the crew disables the undervoltage function manually throughout the plant. However, instead of defeating protection completely, it would be preferable to simply de-sensitize as needed to avoid the expected nuisance interruptions. In this way, a "safety net" level of protection is retained, ensuring proper operation in the event of severe disturbances.

### Preventive Maintenance

As described above, one means for providing improved system protection is to quickly detect and correct disturbances once they occur. A second and perhaps more desirable way to protect a system and improve service continuity is to prevent the abnormal condition in the first place. Preventive maintenance attempts to do just this and can be made more effective through the use of data gathered by an integrated system.

Overload conditions often result from a simple unbalance of loading among individual feeders. By monitoring and recording peak loading on each feeder over time, it can be determined if some breakers are running at or near overload capacity — dangerously close to an overload trip condition that could potentially shut down an area of the facility. (Refer to Figure 2.) Through early diagnosis, the overload condition can be prevented by simply reconnecting one or more of the loads to an under-utilized feeder, or through careful scheduling of temporary loads.

Likewise, examining other trends exhibited by power system data may also prove instructive to prevent future problems. For example, a manufacturer of assembled products adds loads throughout the plant over a five year period. Although none of these loads may appear significant in itself, by examining voltage data collected at its service entrance equipment, a potential problem can be avoided. Seeing that normal voltage levels have dropped well below the nominal system voltage, the plant engineer determines that a change in transformer taps is required to maintain the proper voltage. Without such foresight, the plant may learn this same lesson the hard way — as a result of the failure of some expensive connected equipment.

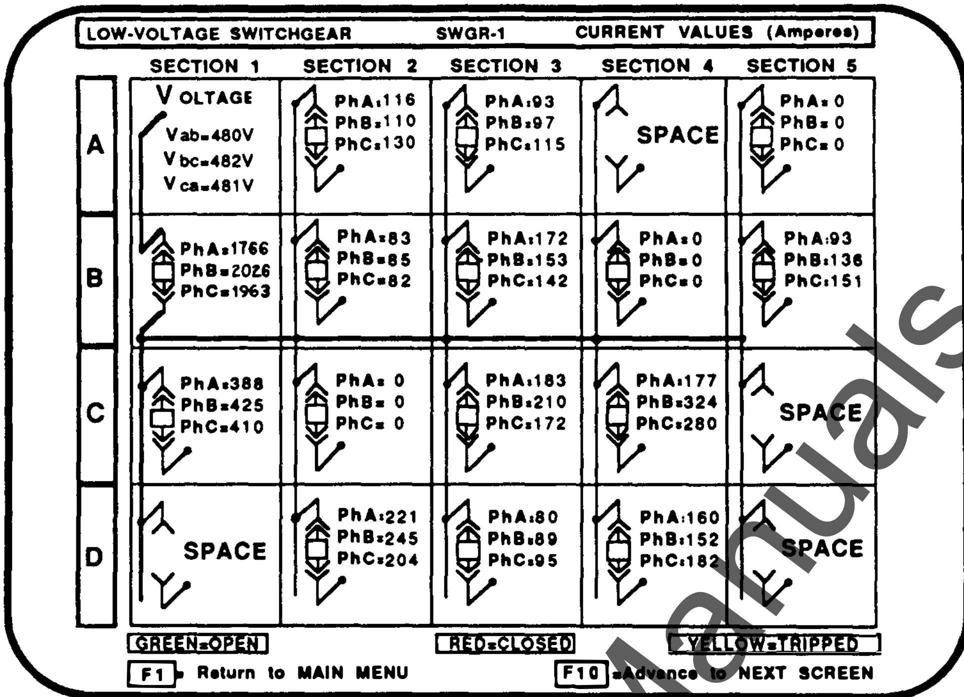


Fig. 2 Graphical displays can provide real-time data and status information for the power system.

The Maritime Administration (MARAD), under contract by the U.S. Navy, has engineered an electronic monitoring system used to schedule maintenance and maximize equipment utilization. A series of auxiliary crane ships utilize two auxiliary generators to supply very large capacity cranes. A system management unit controls load banks for each generator and performs automatic data-logging to equalize wear on the crane motors and to alternate generator use.

Another interesting opportunity for preventive maintenance, given a central means for collecting power system data, involves ground fault current. In solidly-grounded wye electrical services, some small leakage current to ground may be expected. But what if it could be demonstrated that this current had tripled in magnitude over the last week? A possible diagnosis could pinpoint the problem: Perhaps a potential transformer lead has come in contact with live bus, breaking down the dielectric to a point near failure. In this way, the ground fault condition could be corrected prior to its escalation to short circuit levels, with resultant equipment damage.

Even with a normally-functioning system, ground fault current levels may vary over time, depending upon the types of electrical equipment being supplied. By maintaining records which correlate magnitudes of ground fault current with the time of day or day of the week, it may be possible to identify which connected equipment requires attention. This will allow the faulted device to be removed from service for repairs, avoiding damage to itself and the rest of the power system.

### Improved System Diagnostics

In the event a protective device performs its function and interrupts a power circuit, it is important to diagnose the problem and take corrective measures. Often, service interruptions are caused by transient conditions; and occasionally no apparent evidence of abnormal conditions will remain. The symptoms frequently are very difficult to interpret, particularly when several circuit conditions operate in combination. The availability of recorded data to give a "snapshot" of circuit conditions at the time of the disturbance greatly simplifies troubleshooting.

Sometimes symptoms may lead to an obvious, but errant conclusion. A prison facility was experiencing occasional "nuisance trips" by a large low voltage power circuit breaker feeding a single transformer. The tripping occurred when the breaker was first closed, energizing the transformer. However, normal magnetic inrush current was dismissed as a possible cause because the breaker's instantaneous tripping function was set at least 15 times the full load current rating (well above the typical equivalent inrush current of a standard transformer). The prison finally summoned factory representatives from the circuit breaker plant to the job site to repair the (apparently) malfunctioning circuit breaker. However, a diagnostic "snapshot" indicated that the breaker was operating correctly, as a result of current in one phase with magnitude on the order of 20-25 times normal. It was finally discovered that a standard transformer was being used in a step-up application, producing inrush currents about twice that normally expected if it had been wound specifically for this application.

Frequently, a single disturbance in an electrical system will lead to a series of events, a chain reaction of device operations whose sequence is difficult to determine. With a central monitoring system available to record the events and to "time-tag" them as they occur, the diagnostic task is significantly reduced. Such records of cumulative events will usually provide all the clues a good maintenance detective will need to resolve any abnormal conditions quickly and with certainty. Conversely, in the absence of meaningful information, proper corrective measures may be painstakingly discovered only through trial and error, or perhaps not at all.

Given the availability of relevant circuit data, the electrical power distribution system can actually be equipped to help diagnose its own problems. A central monitoring point — an operator control room, guard stations etc. —can be designated for system control. An example of this is illustrated in Figure 3. Here, a graphics screen display is equipped to report various alarm conditions, present pertinent system data, and offer possible troubleshooting options. This allows a less highly skilled operator to maintain the system in the event of a disturbance by incorporating the experience levels of more highly trained individuals. The night watchman may find this system to be much more helpful than a confusing series of warning lights; however, likely to receive the greater benefit is the factory foreman whose sleep remains uninterrupted because the watchman is able to correct the problem himself by following the on-screen directions.

## System Planning Assistance

Earlier, it was suggested that historical tabulations of peak loading on various feeders throughout a power distribution system could be used to prevent overload conditions. This same information can be quite useful when adding loads to existing equipment. Often, in the absence of detailed load information, additional feeders (sometimes entire equipment sections) are purchased to ensure that existing feeders are not overloaded. With accurate loading information available, these expenses may be avoided. Instead, loads are added to those feeders which historically have proven lightly loaded, with confidence that maximum loading levels will not be exceeded.

An analogous situation involves the addition of single-phase loads. (Refer to Figure 4.) By comparing electrical current profiles of all three phases, new single-phase loads can be connected to achieve an optimally balanced system. Similarly, power factor profiles on a per-phase basis may dictate that certain loads be given preference for a particular phase so that the average three-phase power factor is affected positively. Furthermore, it may be possible to determine the time of day when correction measures are needed most. This can assist planning in that certain loads which tend to improve power factor might be scheduled during these periods or cycled accordingly.

The allocation of energy usage costs among departments is gaining in popularity, and many firms have determined this to be a good opportunity to control costs without affecting product quality. An example of how this is being implemented is illustrated in Figure 5.

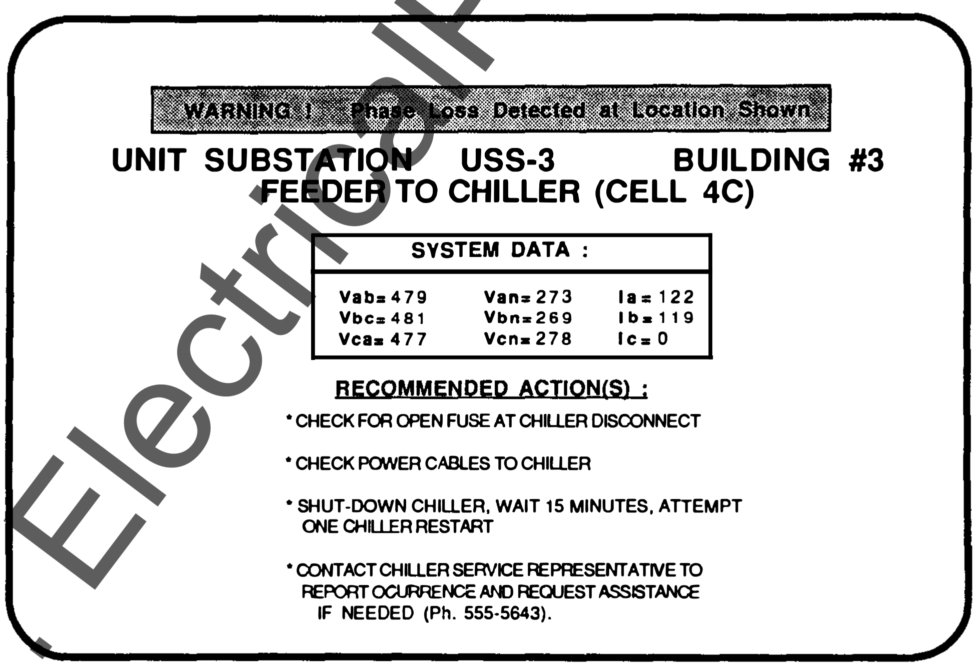


Fig. 3 On-line diagnostic screens assist the system operator to quickly identify power system problems and possible remedies.

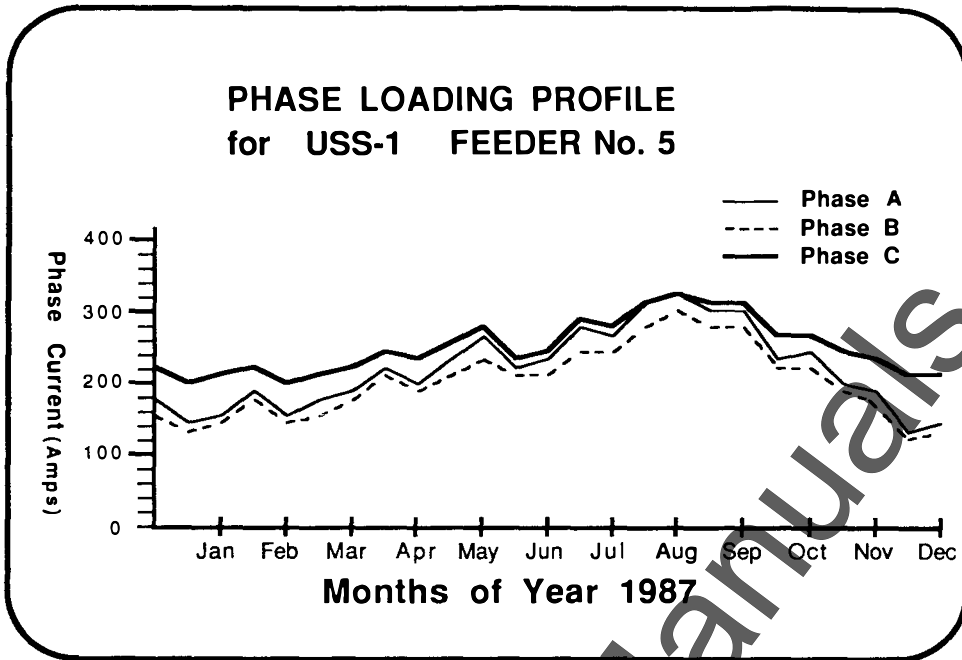


Fig. 4 Power system historical data in graphical format provides extensive system planning assistance.

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| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | DAILY POWER USAGE and COST | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | DATE | PAINT DEPARTMENT | | ASSEMBLY AREA 1 | | ASSEMBLY AREA 2 | | REWORK | | SHIPP |
| 4 | | | | | | | | | | |
| 5 | | KWH | COST $ | KWH | COST $ | KWH | COST $ | KWH | COST $ | KWH |
| 6 | | | | | | | | | | |
| 7 | 9-1-87 | 3274 | 432 | 879 | 156 | 267 | 48 | 159 | 30 | 89 |
| 8 | 9-2-87 | 3841 | 507 | 945 | 168 | 385 | 68 | 136 | 26 | 76 |
| 9 | 9-3-87 | 2866 | 378 | 848 | 151 | 323 | 57 | 148 | 28 | 88 |
| 10 | 9-4-87 | 2957 | 390 | 822 | 146 | 320 | 57 | 166 | 32 | 93 |
| 11 | 9-5-87 | 1845 | 243 | 452 | 80 | 215 | 38 | 132 | 25 | 23 |
| 12 | 9-6-87 | 894 | 118 | 338 | 60 | 174 | 31 | 145 | 28 | 25 |
| 13 | 9-7-87 | 2464 | 325 | 735 | 130 | 327 | 58 | 137 | 26 | 67 |
| 14 | 9-8-87 | 2933 | 387 | 859 | 153 | 353 | 95 | 141 | 27 | 87 |
| 15 | 9-9-87 | 3471 | 458 | 877 | 156 | 349 | 62 | 152 | 29 | 92 |
| 16 | 9-10-87 | 3029 | 399 | 793 | 141 | 337 | 60 | 158 | 30 | 85 |
| 17 | 9-11-87 | 2751 | 363 | 858 | 153 | 287 | 51 | 134 | 26 | 83 |
| 18 | 9-12-87 | 1964 | 259 | 497 | 88 | 205 | 36 | 146 | 28 | 27 |
| 19 | 9-13-87 | 2912 | 384 | 367 | 65 | 165 | 29 | 131 | 25 | 20 |

Fig. 5 Energy usage data imported directly into a spreadsheet program on a personal computer can be used to allocate internal billings and to control energy costs.

Additional opportunities for cost savings may be discovered by monitoring minimum and maximum values for various power and energy parameters, including recording the time of day at which these extremes were encountered. Along these same lines, the energy usage patterns of two similar machines (perhaps by different vendors) may also be monitored for comparison with manufacturers' claims or with each other.

In general, new equipment installations are designed in accordance with consultants' estimates of loading, diversity factors, etc. When new technology equipment is included, it may be difficult to accurately predict demand levels; and equipment may be sized conservatively to ensure adequate ratings. When adding to the original equipment installation, the tendency is to use the same criteria as guidelines for the expansion. However, the availability of reliable historical data should allow the new load assessment to be made with precision. The information collected on similar existing loads serves as a useful tool to size additional equipment.[2] In many cases, this quality data provides a good substitute for years of designing experience and may save a considerable sum in equipment cost. Furthermore, the projected savings can be audited via the same system used to predict the results in the first place!

### Automatic Recordkeeping

The scope of data described thus far is not necessarily beyond the capabilities of conventional systems. However, capturing any more than one or two individual data items generally becomes cost prohibitive. Furthermore, conventional means may suffer inherently from inaccuracies or unwanted side effects which make them prohibitive on this basis. For example, indicating meters are often used to monitor current, voltage, power factor, etc. To accumulate this information, a user must individually record these readings periodically. Other options would be to connect temporary equipment, or install special purpose systems to make this information available over time. Recorded values obtained by sight readings may not represent an accurate sampling, since an unusually high or low reading may or may not be part of the sample. As with the collection of data through special purpose systems, the cost of the data retrieval itself becomes significant. By acquiring data as a by-product of the integrated system, the overhead cost of data collection is spread over the various other protection and control functions also utilizing this information.

Records of energy usage and power demand can be utilized in a number of ways. In some cases, these may provide valuable evidence of the facility's compliance with governmental regulations such as those of the Environmental Protection Agency (EPA) or similar authorities. Records showing loading levels which reflect the operation of a pollution control device, required by the EPA, would indicate clearly its continued operation during a disputed time period. These same records might also be used to show how certain production levels were reduced in a good faith attempt to mitigate pollution problems during times of inoperation for repair or replacement.

Other types of documentation can be made readily available electronically. Consider a hospital which must exercise its emergency generator once a week for testing in order to comply with applicable regulations. This activity could easily be recorded by the integrated system and a maintenance history generated.

Other maintenance data such as the number of breaker operations, number of short-circuit interruptions, cumulative fault duty, etc., can be tabulated and utilized to establish more appropriate maintenance schedules. Instead of performing the same costly maintenance on all protective devices, inspection and testing are tailored closely to actual equipment requirements, thus saving money and improving the effectiveness of the maintenance program.

### Automation Of Control Functions

Through integration of protective devices and instrumentation functions, various control functions can be completely automated. Great flexibility can be achieved in performing a number of system management functions, resulting in a highly efficient power delivery system.

The most popular of all control functions involves automatic transfer schemes, where two or more sources of supply are supervised to ensure at least one available power source at all times. Typically, upon loss of voltage at one main device, the system management unit (after a field adjustable time delay) executes automatic transfer to an alternate main device. The central processing unit can contain safeguards against inadvertent paralleling of sources, closing of any breaker into an overcurrent condition, or transfer to an undervoltage source. An intelligent lineup can also be pre-programmed to perform elaborate interlocking to prevent accidental or malicious operation of the switchgear.

Load shedding and other forms of load prioritizing can be directed by the central processing unit, based on information available through the integrated system. During a low voltage condition, or "brown out", power to critical loads may be maintained by selectively opening feeder and branch circuits supplying non-critical loads. The centralized control system also can be used to cycle non-critical loads — such as water heaters, chillers, etc. Where redundant equipment exists, critical loads may be re-routed by selecting an alternate path to a more reliable source. This type of control requires a knowledge of the entire power distribution system operation and is ideally suited to the integrated systems approach, in which the complete system is under central control. Manual operation of protective devices through remote control is also possible, fully supervised by the central system to avoid inadvertent operation.

The presence of large motors in a power distribution system often warrants extensive automatic control functions. On loss of one phase or in detecting an undervoltage condition, such a system can disconnect and re-energize large motors automatically. This is particularly important when out-of-phase reclosing can subject these motors to extensive damage. Following a loss of source voltage (and once motor residual voltages have been allowed to decay to safe levels), the central system can automatically re-start motors according to a pre-determined sequence with preset time delays, ensuring safe re-energization.

Automatic power factor correction measures represent yet another opportunity for automation of power equipment. By selective switching of capacitor banks, shedding of non-essential loads, and re-direction of various loads, the average system power factor can be corrected to within the limits specified by the local utility, avoiding additional penalty charges. This action can be initiated based on actual power factor levels or predicted levels based on present trends.

Extensive system testing is a positive measure for demonstrating system reliability and identifying potential problem areas. Manual testing, supervised by the central processing unit, and automatic testing can be made an integral part of the control system. This capability encourages frequent system testing and ensures that the proper tests are run to exercise all affected portions of the system. Automatic tests may involve simple transfer of sources upon detection of a simulated undervoltage condition. In more complicated schemes, the transfer may involve a generator startup operation, time delayed response, and source transfer following verification of generator voltage, frequency and speed. By incorporating system testing as a form of preventive maintenance, the overall system reliability is enhanced.

### Increased System Reliability

By adopting an integrated systems approach to power distribution, the overall reliability of service can be greatly increased. When conventional system components fail, this condition can persist undetected until after equipment damage has resulted. Using the system management capability of a central controller, the individual devices can be monitored to verify their readiness to operate as intended. Checks for the presence of control power, continuity of control circuits, and proper contact status may all be used to ensure proper operation of the system. If an abnormal condition is detected, an annunciating alarm can be communicated to a central control room or monitoring station for operator response. In some cases, the system itself may be able to resolve its own problem by automatically resetting parameters, down-loading protective device settings, and re-initializing the process.

To ensure that all protective device settings remain as prescribed and approved, a verification process can be included to compare actual settings with those in the host system memory. This may be helpful where instantaneous trips or ground fault functions have been temporarily desensitized or disabled by maintenance crews which inadvertently fail to return the devices to normal operation. This can also be used to alert the plant engineer of setting discrepancies caused by replacement of existing feeder breakers or relays.

## OUTLOOK FOR THE FUTURE

Power distribution equipment manufacturers have adopted a variety of methods to provide many of the user benefits described in this paper. Many systems are oriented specifically toward applications at either low voltage or medium voltage, but generally not both. It is anticipated, however, that the integrated systems approach to power distribution will extend to all voltage classes in the future. Integrated systems offer protection, instrumentation, and control functions which inherently transcend these boundaries. Future systems will incorporate power system components such as generators, transformers and motors in order to better utilize and protect this equipment. Opportunities for additional user benefits will grow proportionately as these capabilities are expanded to include more of the power distribution system.

In addition, integrated systems present significant opportunities for optimizing equipment utilization by interconnection with other plantwide networks. Energy management systems can perform effectively by using real-time data provided directly from the integrated system. The conventional system of transducers, analog inputs and analog-to-digital converions is replaced with a single digital communications input to furnish the same information. The user may be able to justify the integrated system on this basis alone, realizing significant savings in direct equipment costs.

Through integrated protection, instrumentation, and control systems, the user has at his disposal a greater amount of real-time power system data than ever before. This paper has addressed a number of applications of this technology. In many cases, these are actual successes being implemented by industrial users; others represent potential benefits as envisioned by equipment manufacturers. Just as personal computer hardware has provided a foundation for the software applications that have revolutionized areas of business, the integrated systems equipment itself represents only the starting point. User applications are expected to multiply, as new solutions are linked with familiar problems, and innovative ideas generate entirely new opportunities. Imaginative users will likely lead the way in determining the vast potential afforded by these systems. The automation of industrial power distribution systems at an affordable price is an exciting vision of tomorrow whose time has begun today.

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