Bus Transfer Systems: Requirements, Implementation, and Experiences

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***Abstract*—A bus transfer system is designed to provide process continuity to the loads attached to a motor bus while transferring the bus from one source to another. A successful bus transfer under contingent conditions provides immense value and benefits to continuous process operations that cannot afford an interruption of power supply to plant auxiliaries. This paper describes some real-world bus transfer requirements, implementations, and experiences in thermal power plants and continuous process industry plants. The fast, in-phase, residual voltage, and momentary paralleling transfer methods are described, compared, and evaluated. The spin-down characteristics for different motor buses are analyzed, and the feasibility of the different transfer modes is deduced. Auto- initiation criterion for bus transfer is explored, using a combination of bus undervoltage, underfrequency, and (df/dt) characteristics. Different integrated system requirements, such as monitoring of readiness conditions, breaker failure detection and corrective action logic, and online testing measures, are discussed. The results of the resultant "hot" load trials and their benefits to the system are explained and interpreted. The concept of islanded transfer for grid-free operations of captive generation-load systems is discussed and elaborated.**

***Index Terms*—Automatic bus transfer (ABT), bus transfer system (BTS), continuous process, fast, in-phase, islanding, residual voltage.**

I. INTRODUCTION

A bus transfer system (BTS) is designed to provide process continuity to the loads attached to a motor bus while transferring the bus from one source to another. Such systems find immense use and importance in several critical situations in continuous process industries (petrochemical plants, chemical plants, semiconductor manufacturing plants, paper mills, textile mills, etc.) and fossil-fuel-fired as well as nuclear power generation stations. The BTS directly contributes to saving revenue loss, avoiding large capital losses associated with material wastage on a break in process continuity, and avoiding large operation and maintenance costs and delays associated with process restarts. A BTS also safeguards against potential safety hazards that relate to sudden process interruptions.

Bus transfer is best appreciated by virtue of its automatic operation on the contingency of the old source currently servicing the plant motor load, such that the old source gets disconnected from the motor bus, and the healthy alternate available source gets connected to the motor bus. Such an action that avoids the loss of process continuity is extremely desirable, provided it does not compromise the safety features of the entire system.

Bus transfer has been employed in various power generation and process industry scenarios using different philosophies and methods. Considerable research and survey work has been done in the field in the past [1], [2]. Traditionally, bus transfer has been included in the switchgear package of a typical medium-voltage (MV) installation for power generation utilities and continuous process industries. However, its sphere of influence transcends the electrical systems of the plant, because the efficacy of a BTS directly affects the operations, revenue, and short-term as well as long-term performance parameters of the plant.

A bus transfer operation reflects on three vital parameters of the plant from the operation and maintenance (O&M) point of view: the duration of open-circuit condition of the motor bus, the electrical and mechanical stress endured by the motors and associated equipment during the bus transfer, and the blocking of the BTS during a short-circuit condition at the motor bus. While the first parameter decides the speed with which power feed is restored for plant operations, the second and third parameters affect the safety and reliability aspects of the plant. These considerations merit an in-depth understanding and judicious implementation of such systems.

II. BUS TRANSFER CONFIGURATIONS

A BTS is typically employed in several different switchgear configurations. Two such popular configurations, the main-tie and the main-tie-main schemes, are detailed here.

A. Main–Tie (Two-Breaker Scheme)

The two-breaker scheme is employed to service a single motor bus from two alternate sources. The normal source feeds the motor bus through the main breaker, while the alternate source feeds the motor bus through the tie breaker.

A typical example is that of a thermal power plant, where the unit auxiliaries, such as boiler feed pumps, forced draft and induced draft fans, cooling water pumps, etc., are supplied through unit boards. The configuration in Fig. 1 shows a single unit board, although higher capacity units typically have two or more unit boards.

The unit board can be fed from two sources. The unit auxiliary transformer (UAT) (normal source) supplies locally generated power to run the auxiliaries when the unit incoming

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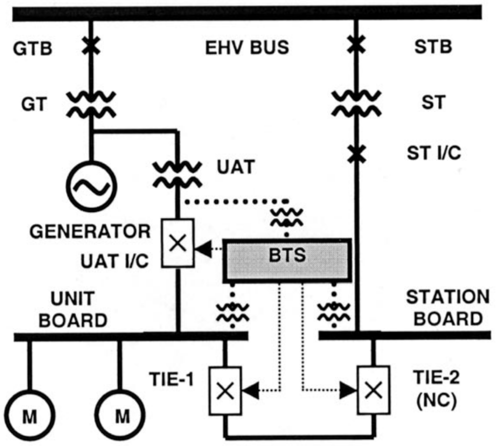

Fig. 1. Thermal power plant: main–tie BTS configuration.

breaker (UAT I/C) is closed. The station board (alternate source) supplies power to the auxiliaries from the grid when both tie breakers (TIE-1 and TIE-2) are closed, and UAT I/C is open.

During startup, the generator transformer breaker (GTB) is open until the generator is synchronized with the grid. Until then, the station board supplies the unit board. After the generator is synchronized, the unit board is transferred to the UAT so that the unit feeds its own auxiliaries. Such a transfer is referred to as a station-to-unit transfer. There are several prioritized and categorized unit tripping conditions such as generator trip, load throw off, turbine trip, boiler trip, etc., under which it is required to automatically transfer the unit board from the UAT to the station board. These transfers are referred to as unit-to-station transfers. Automatic transfers on unhealthy bus conditions determined by different auto-initiation criteria are also employed in order to constantly provide a healthy supply to the motor bus. Manual transfers are commonly conducted during planned startups and shutdowns.

Typical breaker-failure logic safeguards the unit board from a permanent paralleling condition. TIE-2 is a normally closed (NC) breaker, used as a backup measure to safeguard the unit from a dangerous generator back-feed condition, in case both TIE-1 and UAT I/C fail to open.

B. Main–Tie–Main (Three-Breaker Scheme)

Fig. 2 shows a three-breaker scheme employed to service two motor buses from two alternate sources. Each source feeds a single motor bus through its main incoming breaker. A tie breaker is provided for coupling the two motor buses.

A typical example is that of a process industry serviced by two separate stations SOURCE I and SOURCE II off the grid. The SOURCE I transformer is connected through the I/C I incoming breaker to BUS I. Similarly, The SOURCE II transformer is connected through the I/C II incoming breaker to BUS II. BUS I and BUS II are connected using the TIE breaker. There are several bus transfer scenarios depending upon the choice of the normal supply to the motor buses.

1) *NC TIE breaker*: The entire motor bus comprising BUS I and BUS II is transferred between SOURCE I and SOURCE II.

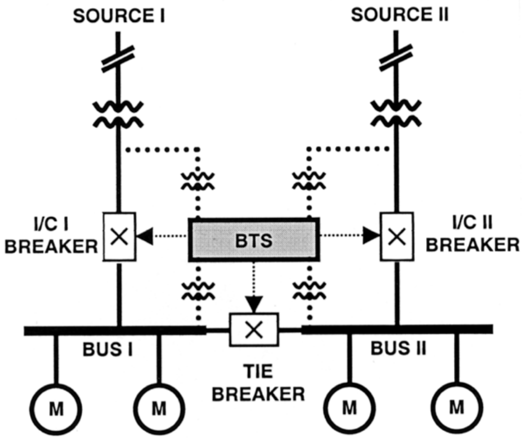

Fig. 2. Process industry: main–tie–main BTS configuration.

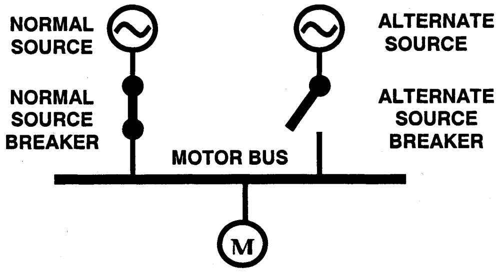

Fig. 3. Simplified bus transfer configuration.

2) *Normally Open TIE breaker*: Each source supplies power to a single motor bus. In case of source failure, the motor bus connected to the failed source is transferred to the source through the TIE breaker.

Since process continuity is the prime consideration in industrial plants, automatic transfers determined by different auto-initiation criteria for source contingencies as well as source equipment failure conditions are employed. Manual transfers are commonly conducted during planned startups and shutdowns. Typical breaker-failure logics safeguard the motor buses from a permanent paralleling position.

III. UNDERSTANDING THE BUS TRANSFER PROBLEM

The fundamental concept of the BTS can be understood using the illustration shown in Fig. 3. Consider a configuration with a normal source connected to a motor bus and an alternate source. The motor bus has a single induction motor connected to it. The impedance of the sources can be considered to be quite small, compared to the motor impedance.[1]

Then, the motor bus transfer can be sequenced in the following two ways.

A. Parallel Transfer

Momentary paralleling is sequenced by first closing the alternate source breaker followed by the opening of the normal source breaker. In this case, both the sources are connected to

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[1] The source impedance could be significant in comparison to the motor impedance if there are two or three step-down transformers between the source and the motor bus. This uncommon condition is not analyzed in this paper.

TABLE I
PARALLEL TRANSFER—COMPARATIVE ANALYSIS

ADVANTAGES	DISADVANTAGES
i) Continuous power to motor bus during transfer permits orderly shutdown of units by eliminating bumps, avoiding motor contactor dropouts and motor overstress.	i) During parallel operation, the increase in available fault current to the motor bus caused by the stronger parallel sources requires either equipment with much higher fault duty ratings or minimized parallel time.
ii) Ease of application and operator understanding.	ii) Will not work when steady state differences of voltage magnitude and/or phase are too large to allow safe transfer
	iii) Cannot be used to transfer when the source to the motor bus is lost due to an electrical fault or abnormal condition.

the motor bus for some duration. Hence, this situation is referred to as momentary paralleling or hot transfer.

A fault occurring in the momentary paralleling situation results in a very serious situation. For example, a fault in the normal source or its transformer will typically be designed to trigger the transfer of the motor bus to the alternate source. However, once paralleled, the alternate source will also feed into the fault. Under most bus system designs, the interrupt ratings for the normal and alternate source circuit breakers and the short-term withstand ratings of the normal and alternate source power transformers will be violated. Similarly, a motor winding fault occurring at the time of transfer will be fed by both the sources. Thus, the alternate source might be exposed to a short circuit during momentary paralleling.[2]

If there is a phase difference between the alternate source and the normal source at the time of the closing of the alternate source breaker, the paralleling will result in a power surge through the bus system which could damage the bus system components. Thus, it is necessary to monitor the phase difference between the motor bus and the alternate source before closing the alternate source breaker. A comparative analysis highlighting the advantages and disadvantages of parallel transfer is given in Table I.

B. Open-Circuit Transfer

Open-circuit transfer is sequenced by first opening the normal source breaker followed by the closing of the alternate source breaker. In this case, the motor bus is connected to neither source for some duration, thus referred to as an open-circuit condition.

1) Spin-Down Characteristics: In an open-circuit condition, the deceleration coupled with decaying trapped air-gap flux in the motor produces a decaying voltage on the motor bus, whose frequency is also continuously dropping. As shown in Fig. 4, before the motor bus is disconnected from the normal source, the motor bus voltage V_{BUS} is identical to the normal source voltage V_{NORMAL}. On the disconnection of the normal source, the motor bus voltage instantaneously becomes the residual voltage of the aggregate motor bus. For a single induction motor case, this is the same as the residual voltage of the motor V_{RESIDUAL}. Due to the load torque angle, V_{RESIDUAL} lags V_{NORMAL} prior to disconnection. In the open circuit condition, V_{RESIDUAL} rotates in a spiral fashion, with decreasing magnitude and decaying phase as shown in Fig. 4.

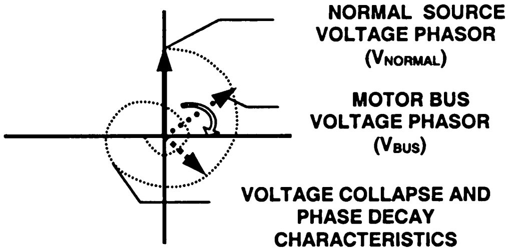

Fig. 4. Spin-down characteristics of an open-circuit motor bus.

The spin-down characteristics depends on the following factors:

1) *Normal Source Integrity*: If the normal source is healthy prior to the opening of the normal source breaker, the motor exhibits standard spin-down characteristics. However, in the event of a normal source fault prior to the transfer (for instance, a three-phase normal source transformer fault), the motor fields get de-energized, which affects the subsequent spin-down characteristics.
2) *Stored Energy and Motor Load Inertia*: In an open-circuit condition, the energy stored in the motor fields continuously decays as it is utilized for spinning the motor shaft. The total rotating inertia acts as a prime mover and delivers energy to the motor bus load and results in a deceleration of the rotating mass. Thus, a high-moment-of-inertia shaft will take longer to spin down than a shaft with lower moment of inertia. Typical high-inertia loads include fans (conventional thermal plants), reactor coolant pumps (nuclear plants), etc. Low-inertia loads include compressors, centrifugal pumps (nuclear and combined cycle plants), high-inertia fans attached to high-voltage buses (thermal plants), etc.

The spin-down characteristics of the motor bus determine the nature of open-circuit bus transfer method feasible for the given system. The analysis of these characteristics is, therefore, an important component of a successful implementation of a BTS.

1) *Simulation and Modeling*: The spin-down characteristics for a given system can be evaluated using modeling and simulation tools [3]–[5]. The combined effect of a motor bus consisting of different motors can be studied in this manner. It is important that the motor model matches the actual response of the motor under a dynamic decaying flux, subnormal frequency condition. However, such modeling may become impractical, due to the lack of relevant motor data available from the plant and/or motor manufacturers.
2) *Event Recording*: A practical, hands-on approach to the characterization of the spin-down is the observation and analysis of an actual spin-down of the motor bus under typical loading conditions. While this gives the required

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[2] Parallel transfer must be blocked when a short circuit occurs either at the motor bus or at the sources.

data unambiguously, it is very difficult to obtain such data specifically for bus transfer studies, since the tripping of the motor bus is essentially a plant trip, which is obviously undesirable in any continuously operating plant. Thus, specific arrangements have to be made to record such data during planned/unplanned shutdowns or during the maintenance period.

Re-Energization: The re-energization of an open circuit motor bus, by means of closing the alternate source circuit breaker, is perhaps the most critical task for an open circuit bus transfer. Several factors need to be considered to avoid potentially damaging transient effects, such as abnormally high inrush currents and shaft torques. The factors that relate to these damaging transient effects are as follows:

1) motor bus residual voltage magnitude;
2) phase angle between the motor bus residual voltage and the alternate source voltage;
3) phase relationship between the oscillating shaft torque and transient electrical air-gap torque, all at the time of re-energization.

Consider the worst case situation, where the alternate source voltage $V_{\mathrm{ALTERNATE}}$ is in phase opposition with V_{BUS} and that V_{BUS} voltage magnitude has not reduced significantly after the motor bus was disconnected from the normal source. The effect of closing the alternate source breaker at this point will be like applying twice the nominal rated voltage to the motor. Upon reconnection, the starting inrush current could be 2 times the normal starting current of the motor, which is about 6–10 times the rated full-load current under the transient conditions and 9 to 15 times the rated full load current under the subtransient conditions. Since the force to which the motor is subjected is proportional to the square of the current, the situation can be extremely damaging. Such forces could loosen the stator coils, loosen the rotor bars of the induction motors, twist a shaft, or even rip the machine from its base plate [6]. The cumulative abnormal magnetic stresses and/or mechanical shock, in the motor windings and to the shaft and couplings, could ultimately lead to premature motor failure due to fatigue. Analysis of re-energization effects require detailed shaft-motor driven load analysis using the Electro-Magnetic Transients Program (EMTP) as prescribed by the NEMA MG-1 1987 standard [7].

These problems motivate the use of appropriate, safe, and reliable bus transfer techniques. A general requirement may, therefore, be defined as follows.

C. Typical Feature Requirements

A BTS typically has the following feature requirements [4].

1) *Process Requirements*
    a) Continuity of electrical service to the loads such that operation of the mechanical process system is not disturbed.
    b) Load shedding should not be required to allow the auxiliary system to reaccelerate.
2) *Electrical Requirements*
    a) Loads should not slow down to the point that large and sustained transient currents are required for motors to reaccelerate.
    b) Excessive transient torques that overstress the motor windings, rotor, shaft, and driven equipment should be avoided.
    c) The BTS should be blocked to operate under a short-circuit condition at the motor bus. For a source short-circuit condition, parallel bus transfer must be blocked. However, an open circuit of the faulted source bus transfer can be allowed under this condition.
    d) There should be no adverse effects on the protection system.
3) *System Requirements*
    a) The required controls should be simple to increase overall reliability.
    b) The BTS should automatically operate on contingency detected by external or internal protective elements. The protective elements should provide fast contingency detection, yet be immune to noncontingency system transients.
    c) The BTS should detect any breaker operation failure during bus transfer and take intelligent corrective action to best meet above process and electrical requirements.

IV. BUS TRANSFER METHODS

The choice of the transfer method plays a critical role in the amount of stress the electrical system may be subjected to during the transfer. The methods differ in the processing, sequencing, and timing related to the closing of the alternate source breaker and the opening of the normal source breaker. The nature of the system dynamic conditions and the nature of the motor loads connected to the motor bus determine the choice of an optimal bus transfer method. The fast transfer method, in-phase transfer method, and the residual voltage transfer method are all open-circuit transfers.

A. Parallel Transfer Method

In this bus transfer method, the alternate source breaker is closed, followed by the opening of the normal source breaker. Thus, during the period of transfer, both the sources are effectively paralleled. Parallel transfer is generally used for startup and planned shutdowns.

It is recommended that the closing of the new source breaker be preceded by a sync-check, which ascertains whether the phase difference between the motor bus and the alternate source voltages is within limits. By blocking a transfer when the phase difference exceeds predefined limits, potentially damaging situations can be avoided.

This method is not recommended for all transfer situations, because it may violate the interrupting ratings for the normal and alternate source circuit breakers and the short-term withstand ratings of the normal and alternate source power transformers.

However, its popularity stems from its ease of application and operator understanding and the delivery of continuous power to the motor bus.

B. Fast Transfer Method

The fast transfer method aims to minimize the open circuit duration of the motor bus, after the normal source breaker is opened. This minimizes the decay in the motor bus voltage and phase, before the alternate source breaker is closed. There are two different kinds of fast transfer methods.

1) *Simultaneous Fast Transfer*: In this method, the control signals for opening the normal source breaker and closing the alternate source breaker are given simultaneously. Typically, a breaker closing time is longer than the opening time. Thus, the motor bus is in an open circuit condition during the transfer. For typical breaker timings, the motor bus dead time might be as low as one or two cycles.
2) *Sequential Fast Transfer*: In this method, the control signals for closing the alternate source breaker is given only after the opening of the normal source breaker is ascertained. In some cases, an early contact which indicates that a breaker is in the process of opening is utilized. Depending on the breaker opening/closing times, motor bus dead times of 5–10 cycles can usually be obtained.

A fast transfer is usually supervised by a sync-check between the alternate source and the motor bus. The sync-check is achieved by comparing the phase difference between the alternate source voltage $V_{\text{ALTERNATE}}$ and the motor bus voltage V_{BUS} to a predefined limit, typically between 20°–35°. Using further processing, it is also possible to estimate the phase difference at the time of alternate source breaker closure in the sequential fast transfer method. This phase difference can be used for a more accurate sync-check in situations with faster dynamics. In several implementations, the ANSI C50.41 –1982 [8], [9] criteria that specifies a maximum of 1.33 p.u. V/Hz across the alternate source breaker before closing is also used to supervise the fast transfer.

The fast-transfer method has the following advantages.

1) The speed of transfer minimizes the interruption of power source to the motor bus.
2) It is a safe, and reliable, as well as economic, method to maintain operation of the motors.
3) Paralleling of the normal and alternate sources is avoided.

C. In-Phase Transfer Method

The in-phase transfer method was first suggested by Young and Dunki-Jacobs [10]. This method comes into use in those cases in which the fast-transfer criteria fails, thus blocking the closing of the alternate source breaker. This leads to a longer open-circuit duration. The spin-down characteristics of the motor bus are important in determining the choice of this motor bus transfer method.

The failure of a fast transfer can happen due to a variety of reasons, such as the following.

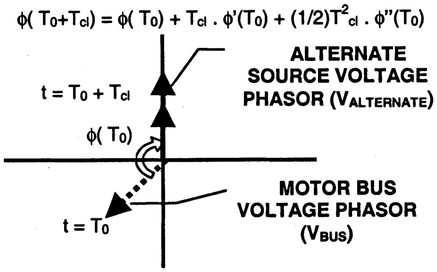

Fig. 5. Phasor plot of an in-phase transfer.

1) Alternate source and normal source are not synchronized or lost synchronization due to system conditions, such as the loss of a tie or a transmission line trip.
2) On disconnection of the normal source, the motor bus voltage phasor differs from the alternate source by a significant angle. This situation might arise even if the normal and alternate sources are synchronized and depend on the motor bus residual voltage characteristics in an open circuit condition.

As described earlier, the motor bus voltage phasor spirals clockwise with respect to the healthy source voltage phasor, as it spins down in the open-circuit condition. Thus, in the event that the fast transfer is not possible, the alternate source breaker closing signal can be timed such that it closes when the phase difference between the motor bus voltage phasor and the alternate source voltage phasor is very small. This will reduce the motor stresses on reconnection since the alternate source is being applied to the motor bus in-phase, and, in certain situations, such a transfer can be smoother than a fast transfer as well.

For instance, consider the situation in Fig. 5. At time $t = T_0$, the motor bus voltage phasor has a phase difference of $\phi(t = T_0)$ with respect to the alternate source breaker. Moreover, assume that the first derivative $\phi'(t = T_0)$ and second derivative $\phi''(t = T_0)$ of this phase difference are also available. Assuming that the closing command for the alternate source breaker is given at $t = T_0$, the limited form of the Taylor's expansion can be used to estimate the phase difference between the motor bus voltage phasor and the alternate source voltage phasor at the time of alternate source breaker closure.

If the phase difference between the motor bus voltage phasor and the alternate source voltage phasor at $(t = T_0 + T_{\text{closing}})$ is estimated to be within predefined limits, then the in-phase transfer method gives the closing command to the alternate source breaker.

Load shedding of the motor bus may be required for in-phase transfer, depending on the characteristics of the motors connected to the motor bus. A detailed analysis of the behavior of the motor bus in the open-circuit condition is required to ascertain the use of such load shedding. However, the main advantage of the in-phase transfer method is the ability to safely transfer the motor bus to the alternate source even if the fast transfer is blocked, without necessarily having to shed load. In many situations, this may also justify the addition of suitable loads such as synchronous generators, high-inertia flywheels, and voltage-supporting capacitor banks to assure smooth in-phase motor bus transfers.

D. Residual Voltage Transfer Method

The residual voltage transfer method is the slowest transfer of the motor bus to the alternate source. The motor bus is allowed to remain in the open-circuit condition, until the motor bus voltage magnitude decays to acceptable levels, usually 20%–25% of its rated voltage. The alternate source breaker is then connected to the motor bus, regardless of the phase difference between the alternate source voltage phasor and the motor bus voltage phasor. Thus, the worst case voltage that could be applied to the motors would have an acceptable upper limit. Planned load shedding is quite commonly used before residual voltage transfer. For instance, the large motor loads that slowed down significantly during the open-circuit condition will draw large currents upon the transfer of the motor bus to the alternate source. Such a situation can trigger an overcurrent trip of the alternate source breaker.

V. BUS TRANSFER INITIATION

The need of a bus transfer can be motivated by a variety of reasons. Thus, the means of initiating a bus transfer can be further classified as manual, protective, or auto transfer.

A. Manual Transfer

Manual transfer is used for planned transfers during startup, shutdown, or certain kinds of maintenance activities of the plant. The actuating mechanisms may be either local or remote using SCADA systems over a communication link. The combination of backup transfer method(s) (e.g., fast–in-phase–residual voltage) is also required to be manually selected before actuation.

B. Protective Transfer

The protective transfer(s) are initiated automatically on the pickup of different protective relay elements input to the BTS. For instance, a main–tie configuration BTS in a thermal power plant has Class A (generator trip, load throw-off) and Class B (turbine and boiler trips) inputs, which actuate immediate changeover of the unit board from the UAT to the station board. Since Class B trips actually cause unit tripping when the reverse power relay operates, corresponding bus transfer can also be suitably coordinated. Similarly, a main–tie–main configuration BTS in a continuous process industry has incoming source transformer trip and transmission line trip condition logic inputs for protective transfers.

C. Auto Transfer

Modern microprocessor-based protection systems offer the digital processing capabilities required to do continuous intelligent system monitoring in real time. Auto transfer initiation logic use these processing capabilities on the bus PT voltage inputs in order to determine the healthiness of the bus. Thus, auto transfer initiation criteria are established based on undervoltage, overvoltage, underfrequency, overfrequency, (df/dt) limits, etc., or many combinations thereof. The ultimate choice of the auto-initiation criteria is determined by the speed and reliability of its response to detect contingencies and its immunity to noncontingency system transients.

VI. BTS INTEGRATED REQUIREMENTS

A complete and integrated BTS solution also needs to meet certain key requirements.

A. Monitoring BTS Readiness Conditions

Since the BTS performs system critical activities, it is typically recommended to continuously monitor the status of certain system conditions as a precondition to ascertaining its readiness to conduct bus transfer. These usually include the following:

1) breaker status (52a, 52b consistency);
2) valid system breaker configuration state;
3) breaker in service condition (75S);
4) PT fuse failure condition (98X);
5) PT cubicle in service position (75S)
6) in-circuit monitoring of breaker trip/close circuits;
7) breaker overcurrent condition (86A);
8) new source voltage/frequency healthiness.

B. Breaker Failure Detection and Corrective Action

A breaker may fail to operate due to electrical and/or mechanical reasons during a bus transfer. This may result in dead bus/permanent paralleling, depending upon the failure of closing of new source breaker or opening of old source breaker respectively. Such a situation may be detected from the monitoring of the breaker NO/NC status inputs (52a, 52b) and/or the current flowing in the old source breaker and the new source breaker.

In the event of a permanent paralleling condition, the recently closed new source breaker is tripped. If this breaker fails to open as well, further upstream breakers may be sent tripping commands. Such an extreme event was experienced by the author (2) in 1982 and resulted in a dangerous generation backfeed condition for a 210-MW thermal power generation unit with a main–tie BTS configuration. This consideration needs to be taken into account before deciding on the type of switchgear for backup measures. In this situation, the station tie is preferred to be a breaker rather than an isolator, along with incorporation of corresponding control logic to trip the station tie breaker if both the UAT incoming and TIE breaker do not open on their respective tripping commands.

In the event of a dead bus condition (failure to close of new source breaker), the bus exhibits spin-down characteristics as discussed earlier. Correspondingly, depending on the detection time for the dead bus condition, it may be possible to reclose the old source breaker (provided it is healthy) in the fast/in-phase/residual voltage mode. The in-phase mode is most likely in this situation, since the phase drift would normally be expected to be significant before new source breaker closure failure is detected. A successful closing of the old source breaker using the in-phase method can keep the bus energized. This can help increase the operator confidence for opting for safer open circuit condition-based fast transfers even for manual/planned bus transfers, wherein parallel transfers were used earlier.

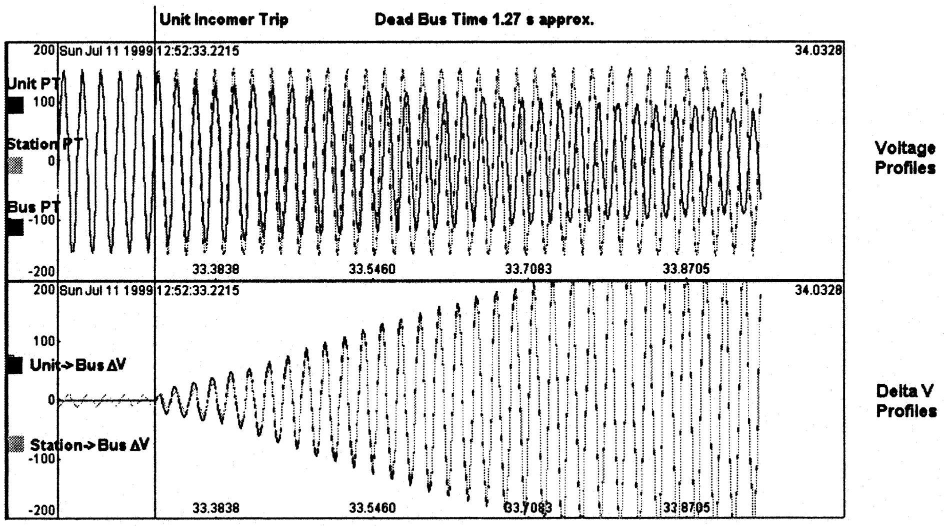

Fig. 6. Unit board spin-down characteristics in a thermal power plant.

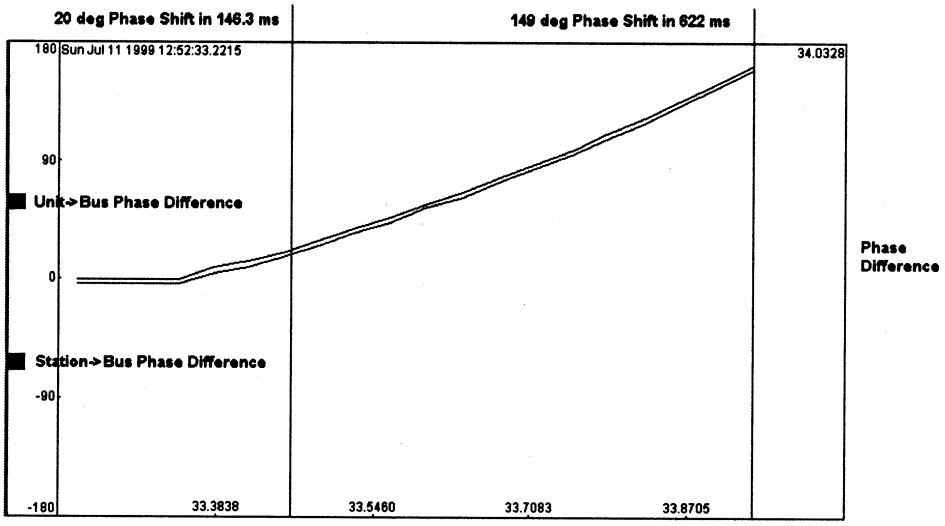

Fig. 7. Phase drift of a unit board during spin down.

C. Online Testing

The online testing of the BTS enables the operator to periodically ascertain if all the functions of the BTS are operating healthily. It is also possible to operate, monitor, and consequently report the operation of the respective breaker tripping and closing contacts, after the insertion of a high resistance in series to these contacts during this test mode. This fictitious bus transfer gives the operator the highest degree of confidence, before actuating a planned manual bus transfer under the existing system conditions.

VII. IMPLEMENTATION AND EXPERIENCES

The data, observations, and analysis described in this paper were obtained by live bus transfer operations [11], [12]. The ability of modern microprocessor-based protection relay platforms to provide monitoring facilities such as event recording, oscillography, and step-by-step replay, along with the basic protection and control functions, has been utilized to a large extent for the same.

A. Thermal Power Plant

A BTS is desirable for thermal power plants because it transfers all the critical auxiliaries to the healthy station source on the occurrence of a unit trip. Thus, the unit can be restored quickly, reducing its overall down time. This faster recovery saves substantial losses in revenue as well as provides vital power generation and/or reserves in an expeditious manner.

The motor bus for the thermal power station auxiliaries are primarily characterized by the presence of large high-inertia fan loads such as forced draft and induced draft fans, and low-inertia pump loads such as boiler feed pump, cooling water pump, etc.

The spin-down characteristics in Fig. 6 were obtained by tripping a lightly loaded unit board during normal unit operations at a 210-MW unit. It may be observed from Figs. 6 and 7 that, due to the high-inertia characteristics of the motor bus, the bus voltage and phase difference decayed gradually. The motor bus took 240 ms for the bus voltage to drop to 80% of its rated voltage and 146 ms to be more than 20° out of synchronism with respect to its normal source before tripping. Thus, a fast transfer

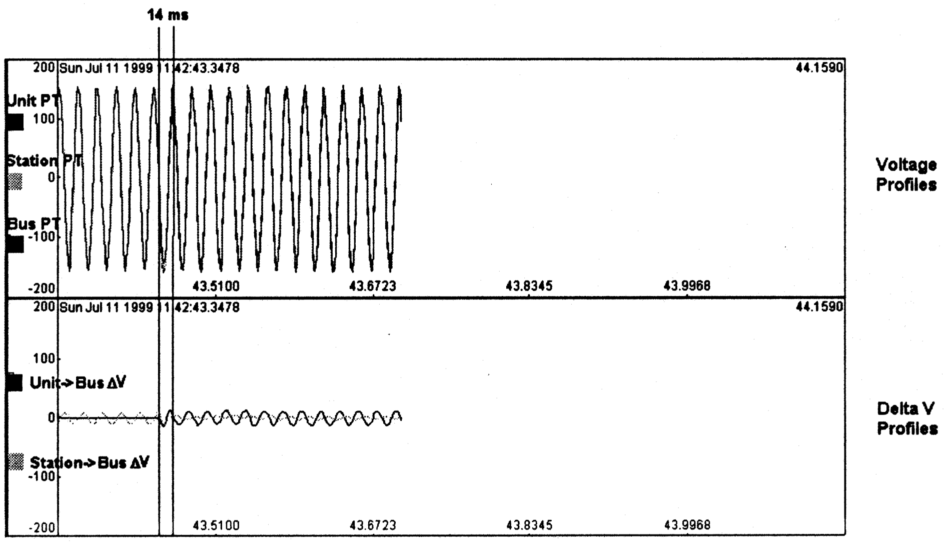

Fig. 8. Fast transfer of a unit board in a thermal power plant.

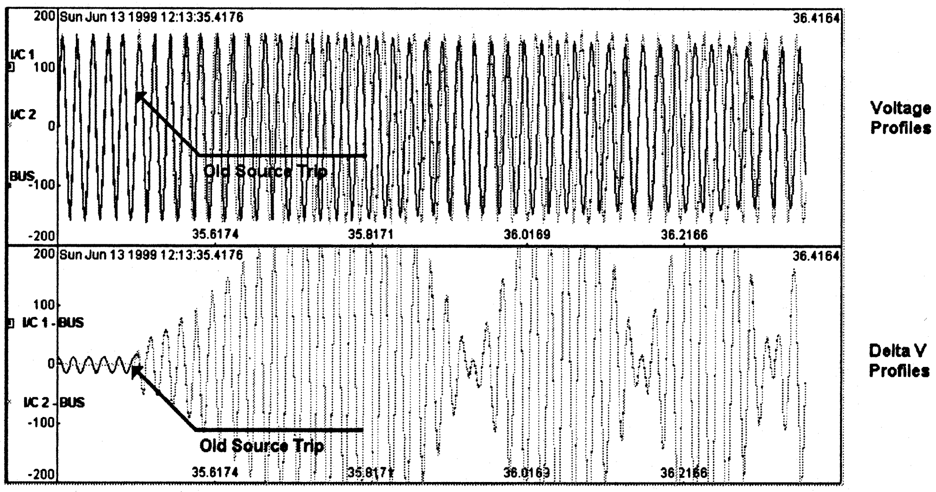

Fig. 9. Spin-down characteristics of a low-inertia bus in a process industry.

can be deemed suitable for a safe and smooth bus transfer operation with no interruption to the unit auxiliaries.

A simultaneous fast transfer of the unit board is shown in Fig. 8. The dead bus time for the unit board was less than a cycle, which resulted in a safe and fast bus transfer with minimal loss of synchronism before re-energization.

B. Continuous Process Industry Auxiliaries

A BTS is desirable for those continuous process industries with at least two alternate independent sources of instantaneous demand power where each plant trip results in substantial loss of material, production, and O&M.

The motor bus for continuous process industries cannot be singularly characterized, since each process demands different sets of motor configurations. However, typical installations consist of varying proportions of MV and low-voltage (LV) induction motor loads, compressor loads, pump loads, agitators, etc. Very often, significant amounts of capacitor banks are connected to the bus for reactive power support as per utility power-factor requirements. These capacitor banks provide support to the bus voltage during the spin-down of the motor bus.

The spin-down characteristics in Fig. 9 were obtained from live bus transfer trials under full-load conditions at a continuously operating polyvinyl chloride (PVC) resin plant. The plant has two incoming 220-kV lines from different substations. The plant is susceptible to trips due to electrical faults, which are accentuated by the hilly topography and humid and rainy climactic conditions in the region.

The 10.7-MW load consisted of a significant amount of low-inertia HV compressor load, along with other HV and LV pump, fan, agitator, and motor loads. An 8-Mvar capacitor bank was connected to the bus for power-factor compensation. It was observed that while the capacitor banks supported the bus voltage very well during the spin-down, the low-inertia load resulted in

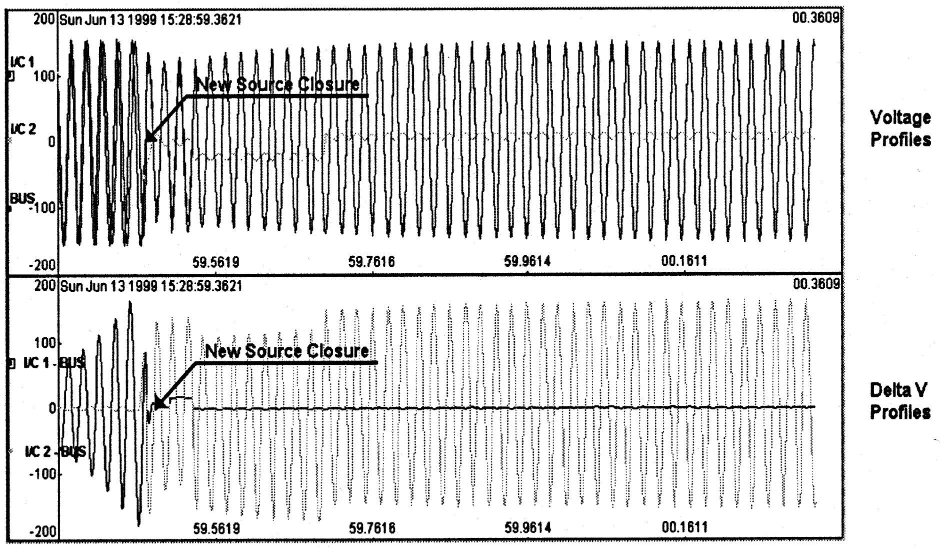

Fig. 10. Fast transfer of a low-inertia bus in a process industry after auto-initiation using instantaneous df/dt criterion.

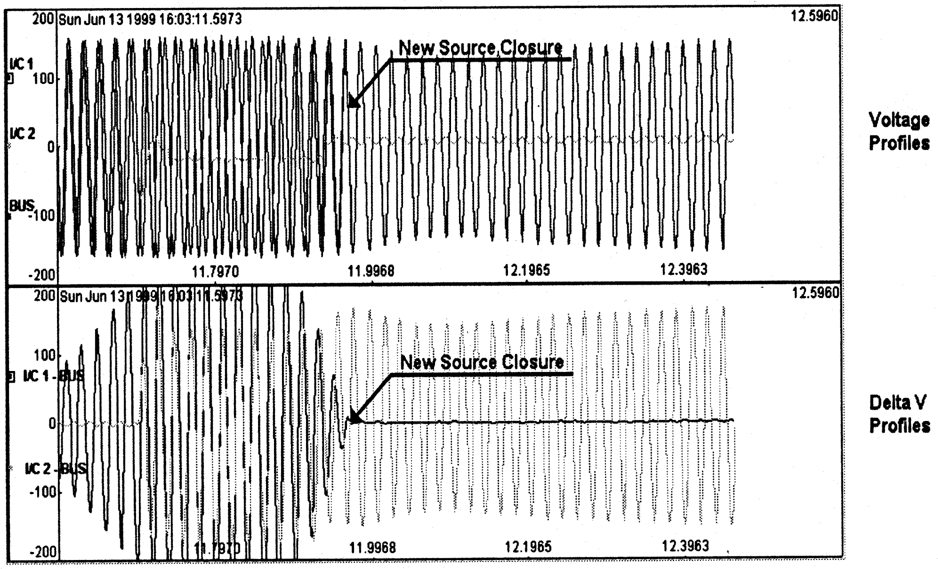

Fig. 11. In-phase transfer of a low-iinertia bus in a process industry after auto-initiation using instantaneous df/dt criterion.

a brisk fall in bus frequency. The bus underwent an entire slip cycle with respect to its alternate healthy source within 21 cycles. Due to this rapid loss of synchronism coupled with a sustained bus voltage, both fast transfer as well as in-phase transfer were deemed suitable.

Unlike the thermal power plant scenario where a contingency was relayed to the BTS, the BTS was required to self-detect the onset of supply contingency. Among several available criteria such as undervoltage, underfrequency, and df/dt, the instantaneous df/dt criterion was deemed suitable as the fastest indicator of contingency and required about 3–4 cycles for detecting supply contingency. For purposes of the live trial, the tripping of the 220-kV incoming breakers of the plant was done to induce the contingency.

A simultaneous fast transfer of this motor bus is shown in Fig. 10. The total dead bus time of about 7 cycles includes about 4 cycles for the detection of supply contingency and about 3 cycles for the closing of the alternate source breaker. The bus drifted by 60° at a very high rate of approximately 10° per cycle before re-energization. The bus transfer was successful in maintaining the process continuity of the plant.

An in-phase transfer of the motor bus is shown in Fig. 11. The in-phase transfer sent an advanced closing command to the breaker such that the breaker closed when the rapidly dying bus was in near-synchronism with the alternate source with 21 cycles of dead bus time before re-energization. The bus transfer was successful in maintaining the process continuity of the plant.

It is worthwhile to mention here that traditional motor protection does not take into account such possibilities of simultaneous re-acceleration of the motors after a short amount of spin-down, as achieved by high-speed motor bus transfer. Thus, the I_{Stall} setting, which permits high currents into the motor only during startup, may trip the motor on re-energization. Hence, the I_{Stall} setting and/or corresponding delay of the motor protection relays may need to be increased to accommodate high-speed bus transfers, without actually compromising on the inherent protection of the motors.

VIII. ISLANDED TRANSFER

An islanded transfer has the capability to transfer between two asynchronous sources, such as the co-generation unit and the grid or an islanded turbine operation, while maintaining process continuity.

A. Islanded Turbine Operation at House Load

In the case of an islanded turbine operation, modern turbines are able to sustain operations at house load for a few hours. This feature is especially pertinent during grid failure conditions and their recovery/restoration. During this system, the grid/station board and the unit board sources are asynchronous with respect to each other.

In the instance of a contingency of a turbine trip during such operations, or a planned load transfer of the unit board to the station, the islanded transfer can use the IN PHASE mode to trip the incoming breaker coming from the unit auxiliary transformer and send an advanced closing command to the station tie breaker, so that it closes at the zero-crossing instance of the slip between the grid and the unit board. It is worthwhile to note here that such a transfer is not possible using the fast method of transfer, as it is not recommended to perform a fast transfer between two nonsynchronous sources or equivalent.

Thus, the real advantage of the turbines now capable of islanded house load operations, can be most advantageously used with such an islanded transfer operation capability.

B. Cogeneration Plant

Consider the case of a plant with a cogeneration unit that prefers to operate in isolation from the grid, using its cogeneration unit for economy, reliability, or regulation considerations. While the incentive for a cogeneration unit to tie to the grid is to earn from the export of power, it is very difficult to isolate the plant from the grid in the event of a grid contingency. Thus, a grid failure, which may be frequent, automatically results in loss of expensive plant processes.

Alternately, consider the case of islanded operation of a plant with islanded transfer capability, wherein the cogeneration unit feeds all the plant auxiliaries. Thus the grid may not be in sync with the cogeneration, with independent frequency and voltages, resulting in continuous slip cycles between the two. In the instance of a considerably infrequent contingency of the cogeneration unit, the islanded transfer uses the in-phase mode to trip the incoming breaker coming from the cogeneration unit and send an advanced closing command to the grid incoming breaker so that it closes at the zero-crossing instance of the slip between the grid and the dying combined plant bus.

Thus the grid can serve only as a backup measure while reliable operations of the plant and its power situations are significantly within the controls of the plant operation.

IX. CONCLUSIONS

The use of a high-speed BTS is very effective and beneficial to mitigate the problems related to the loss of process continuity in continuous process plants. The availability of an alternative source of supply can be best utilized if a high-speed BTS is used to transfer the motor bus from the normal source of supply to the alternative source, in the event of a contingency of the normal source. This can provide enormous savings in revenue, plant load factor and O&M expenditure in the short term, while reducing motor maintenance in the long term. Live trials have proven the high-speed bus transfer technology and its significant benefits in both utility power plants as well as continuous process industries. An islanded transfer operation has been shown to be beneficial for islanded turbine operations under house load conditions and for reliable grid-free operations of plants cogeneration utilities.

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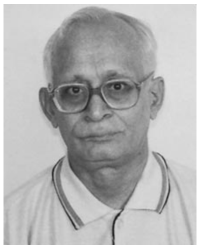

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