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Considerations and Methods for an Effective Fast Bus Transfer System

Girish Hunswadkar, N.R. Viju
Easun Reyrolle Ltd.

Abstract

A Fast Bus Transfer is the process of disconnecting a motor bus from the present source of power and effectively reconnecting to an alternate source of power within the minimum possible time to guarantee process continuity. A fast and successful bus transfer enables continuity of critical processes, thereby enabling the plant or industry to minimize losses due to unavoidable transfers or contingencies. This paper discusses the considerations and methods to be taken for effectively carrying out a successful bus transfer, whether it is planned or is an emergency.

Key Words

FBT – Fast Bus Transfer, MBT – Motor Bus Transfer, UAT – Unit Auxiliary Transformer, SST – Station Service Transformer, V/Hz – Voltage to Frequency Ratio, PU – Per Unit, HMI – Human Machine Interface

1. Introduction

Most power plants and industrial plants have motors of various sizes and capacities that must remain operational for various process and economic reasons. Unexpected power interruptions on continuous production lines, like in chemical plants, papermaking industry, automotive or semiconductor business can cause serious damage to key equipments which can have severe economic consequences and will affect process continuity. Similarly, in power plants, power interruptions to the plant auxiliaries can result in generation loss.

To address this situation, most facilities employ two power sources to supply the plant auxiliaries. In a power plant these sources could be the station service transformer and the auxiliary startup transformer. In a process plant there could be two separate power sources feeding separate sections of the plant. To maintain plant operation and process continuity, motor buses may require transfer from the running/present source to an alternate source. In power plants transfer of sources will be required both in planned and emergency situations. Motor Bus Transfer schemes and systems are employed to maintain process continuity in processes served by large motors or aggregates of smaller and large motors. Larger motors, of both the synchronous and induction type, may require comprehensive, integrated source transfer strategies in order to avoid mechanical damage. The coast down period and resultant voltage and frequency decay may take seconds, and unsupervised source transfer may cause damage. During an improper transfer, mechanical damage may occur in the motor, the coupling to the load or to the load itself, and is primarily caused by excessive shaft torques. The total mission of a MBT system is not only to maintain process continuity but also to effect source transfers so as not to cause any damage to the motors and connected loads. This paper discusses the various considerations and methods to be taken for a successful and effective bus transfer.

2. Typical Plant Layouts

2.1 Two breaker schemes

Typically, generating plants have at least two sources of power for the auxiliary equipments associated with each generating unit. Atypical unit connected motor generator bus system is shown in figure 1. While the generating plant is in normal operation, the power needed by the auxiliary systems associated with the generator would be supplied by the Unit Auxiliary Transformer (UAT) connected to the bus between the generator terminals and the step up transformer (if available). In this plant layout, the plant auxiliaries must be supported with an alternate power source during normal unit start up and shut down sequences, as well when the UAT has to taken out for maintenance or need to be disconnected because of system or generator faults. During these instances, the Station Service Transformer (SST) which is connected to the grid should cater to the power requirements of the auxiliaries. This is commonly called a Two breaker scheme.

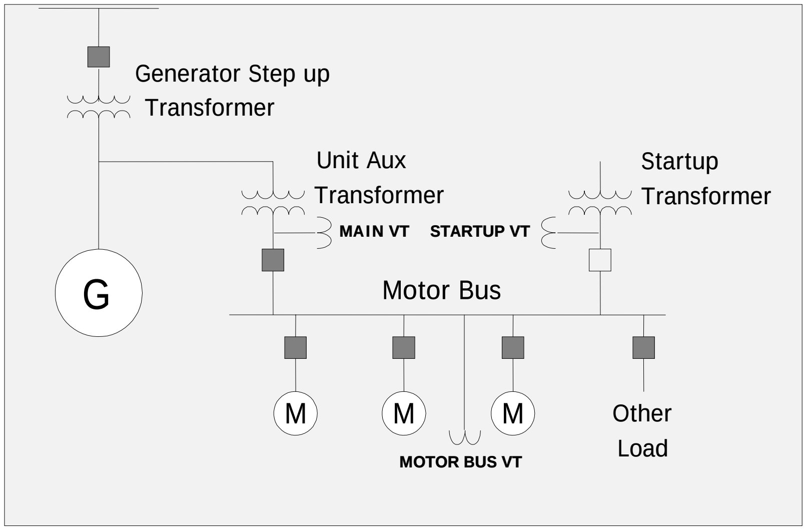

Figure 1 - Unit Connected Generator Motor Bus - Two Breaker Configuration

During the plant startup process, the generator transformer breaker (GTB) is open until the generator is synchronized with the grid. Until then, the feed from the SST supplies the unit auxiliaries. Once the generator is synchronized, the unit board is transferred to the UAT Incomer source so that the unit feeds its own auxiliaries during normal plant running conditions. This transfer is called as a Station-to-Unit transfer. In the event of a generator trip, load throw off, turbine trip, boiler trip etc., it is required to automatically transfer the unit board from the UAT Incomer to the alternate feed available from the SST. This transfer is called as Unit-to-Station transfer.

2.2 Three breaker schemes

In case of a combined cycle power plant or a typical process industry, there could be two separate sources from the utility supply system grid. As can be seen in Figure 2, The Incomer-1 is connected to Bus-1 and Incomer-2 is connected to Bus-2. Bus-1 and Bus-2 are interconnected through a Tie breaker, which could normally be open. This is typically called a Three Breaker configuration.

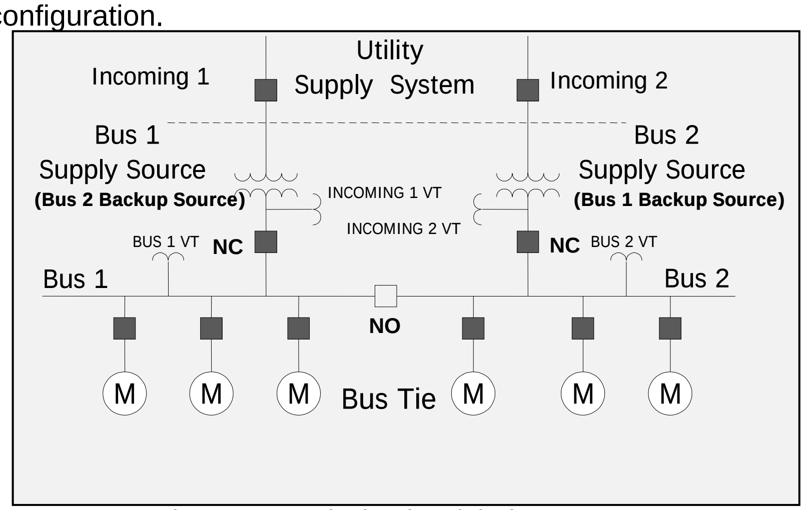

Figure 2 – Typical Industrial Plant Motor Bus

There are several bus transfer possibilities depending upon the choice of the Incoming feed to the motor buses. In case of a normally closed Tie breaker, the complete load including motor bus 1 and 2 is transferred between Incomer Sources 1 and 2. If the Tie breaker is normally open, Incomer Source 1 and 2 supplies power to its own motor buses independently. If any one of the sources fail or trip, the motor bus connected to the failed/tripped source is transferred to the other source by closing the Tie breaker.

3. Considerations for Motor Bus Transfer

In a High Speed Motor Bus Transfer System, there are three main parameters of the plant which need due consideration from the point of view of Operations and Maintenance viz. the Ring down / Coasting down duration of the bus voltage in the open circuit condition, the Electrical and Mechanical stresses exerted on the motors and the connected loads during the source transfer and the High Speed Motor Bus Transfer System Lockout / Blocking during a short circuit condition at the motor bus. While the first parameter decides the speed of the changeover with which the alternate source is connected to the bus and system is restored, the second and third parameters affect the safety and reliability aspects of the plant equipments and process.

3.1 Spin down or Coast down of Motor Bus

When a breaker is opened and the bus is disconnected from the Source (Source-1), the motors connected on the bus start decelerating and the decaying trapped air gap flux in the motors produce a decaying emf on the motor bus, whose frequency is continuously dropping. Therefore the coasting down emf of the motor bus Vbus rotates with decreasing magnitude and decaying phase. The spin down characteristics depends on the following factors.

1. **Characteristics of Motor and Load:** The larger the size of an induction motor is, the longer it will take the voltage to decay. The higher the load on the motor is, the faster the motor bus frequency will decay. If the inertia of the aggregate motor loads on the bus is high, the motor bus frequency will decay slowly during the coast down period. This has a direct impact on how fast the phase angle changes. Low inertia loads will result in change of the phase angle, as the frequency of motor bus decays faster, thereby the slip frequency between the motor bus and the new source quickly increases.

   Voltage will tend to decay much more rapidly on a motor bus with all induction motors. On a motor bus with a mix of synchronous and induction motors, the synchronous motors will attempt to hold up the voltage during the transfer interval.

   During the disconnected coasting down period, the energy stored in the motor fields continuously decay 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 deceleration. 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 in thermal plants, Coolant pumps in nuclear plants, etc. Low-Inertia loads include Compressors, Centrifugal Pumps in nuclear and combined cycle plants, etc. The typical voltage and phase angle decay of the characteristics of High inertia and Low inertia motors are shown in the Figure 4. This spin-down characteristics of the motor bus determine the nature of open transition bus transfer method (discussed in the subsequent sections of this paper) feasible for the given system.

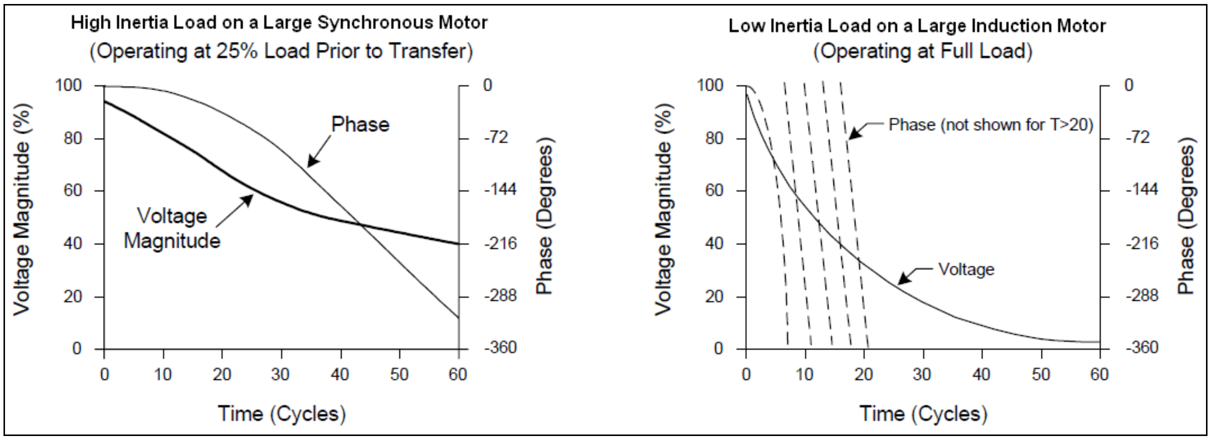

Figure 4 - Voltage and Phase angle decay characteristics of High and Low inertia motors

2. **Resultant Voltage Frequency ratio (V/Hz):** Pursuant to the phase angle and voltage, and their effect on resultant V/Hz, some generalizations can be made. As the phase angle increases between the two sources, the V/Hz will increase (assuming the two source voltages are the same). As the voltage difference between the two sources increases, the V/Hz will increase (assuming the phase angle between the sources remains the same).

   According to IEEE/ANSI Standard C50.41-2000 for Fast Motor Bus Transfer System, the Resultant V/Hz at the instant of a transfer should be less than1.33 per unit (pu).

On the whole considering the above points, the re-energization of a spinning down motor bus, by closing the alternate Source-2 circuit breaker, is the most critical task for an open transition bus transfer system. Several factors need to be considered, in order 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:

- Magnitude of the residual voltage, between the motor and the bus.
- Phase angle between the motor bus residual voltage and the alternate source (Source-2) voltage.
- The resultant Volts/Hertz applied across the motors, at the time of re-energization.

Consider the worst case situation, where the alternate Source-2 voltage V2 is in phase opposition to the spinning down bus voltage Vbus and that Vbus voltage magnitude has not reduced significantly after the bus was disconnected from the present source (Source-1). The effect of closing the alternate source breaker at this point will be like applying twice the nominal rated voltage to the motor. Upon re-connection, the starting inrush current could be 2 times the normal starting current of the motor, which is about 6 to 10 times the rated full-load current under transient conditions and 9 to 15 times the rated full load current under sub transient 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 windings, loosen the rotor bars of the induction motors, twist the shaft, or even rip the machine from its base plate. The cumulative abnormal magnetic stresses and/or mechanical shocks, in the motor windings and to the shaft and couplings, could ultimately lead to premature motor failure owing to fatigue.
The damages that can result from an untimed bus transfer as mentioned in the previous paragraph motivate the use of Comprehensive, Safe and Reliable techniques and methods of Fast Motor Bus Transfer. The total mission of a High Speed Motor Bus Transfer System is not

only to maintain process continuity but also to effect source transfers so as not to cause any damage to the bus, motors and to the connected loads.

4. Methods of Motor Bus Transfer

Based on the Process, Sequence and Timing of opening of the present Source-1 breaker and closing of the alternate Source-2 breaker, the Motor Bus Transfer methods are classified into two types.

1. **Closed Transition:** This is a Make-before-Break transfer operation with momentary paralleling of both the sources referred also as 'Hot Parallel Transfer'.
2. **Open Transition:** This is a Break-before-Make transfer operation without paralleling of both the sources. There are four methods by which the open transition Motor Bus Transfer is executed.
    a. Fast Transfer
    b. In-Phase Transfer
    c. Residual Voltage Transfer
    d. Fixed Time Transfer

    There are two modes of operation in an Open Transition Fast Transfer.
    a. Sequential Mode
    b. Simultaneous Mode

We shall discuss each of these methods one by one, their advantages and disadvantages.

4.1. Closed Transition - Hot Parallel transfer

In a hot parallel transfer, the new source is connected to the motor bus before the old source is tripped, as shown in Figure 5. The intent is to transfer sources without interruption. The phase angle, delta voltage and delta frequency from the motor bus and the new source are evaluated prior to the transfer, to assure that the motor bus and the new source are in synchronism. This method has gained wide acceptance for routine source transfers because transients on the motor buses are eliminated.

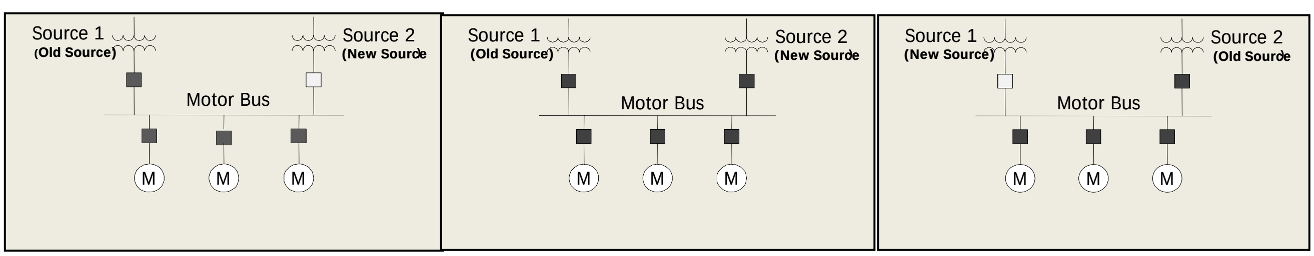

Figure 5. Sequence of Hot Parallel Bus Transfer

Auto Trip provisions must be incorporated such that, if the new source breaker is closed but the old source breaker remains closed, the transfer system must immediately trip the old source breaker. This allows parallel transfer but prohibits inadvertent parallel operation. Alternatively, Auto Trip provisions can be provided to trip the new source breaker that may have been inadvertently closed.

Hot Parallel Transfer - Advantages

- No disruption in plant process.
- Simple to implement with synchronizing check relay supervision across new source breaker.

- No transient torque on motors during the transfer.

Hot Parallel Transfer - Disadvantages

- Cannot be used to transfer when the source to the motor bus is lost due to an electrical fault or abnormal condition.
- There may be instances where the two sources may not be derived from the same primary source and a large standing phase angle may be present between them, precluding a hot parallel transfer.
- Assuming the phase angle relationships of the two sources is acceptable, with the two sources paralleled; currents flowing into and through the bus may violate the interrupt rating of the circuit breakers and short term rating of the source transformers.
- A fault occurring either on the bus or on the sources during the time the sources are paralleled can overstress the components of the bus system. The probability of this happening may be viewed as small; however, the consequences of such a fault occurring during the sources paralleled operating interval should be thoroughly evaluated before the hot parallel transfer system is used.

Considering the above points the design of the Fast Motor Bus Transfer System must ensure the source parallel condition is temporary.

4.2. Open Transition – Fast, In-Phase, Residual Voltage Transfer and Fixed Time Transfer
Figure .6 shows the sequence involved in an Open Transition Bus Transfer.

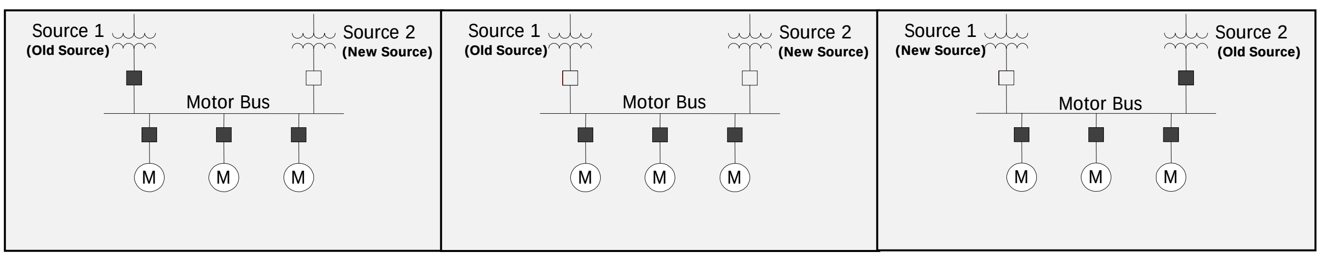

Figure 6 – Sequence in Open Transition

4.2.1. Fast Transfer

The main aim of the Fast Transfer is to minimize the dead time of the motor bus, when the present source (Source-1) breaker is opened. This minimizes the motor bus voltage and phase decay before the new source (Source-2) breaker is closed. The new source breaker will be closed by the Fast Transfer method if the phase angle between the motor bus and the new source is within or moves into the phase angle limit during the Fast Transfer Enable (Time) Window. One cycle phase angle response is required by the Bus Transfer system to issue a close command to new source breaker or to block closing if the phase angle goes out of permissive limit. Closing shall also be supervised by an Upper and Lower Voltage Limit check on the new source.

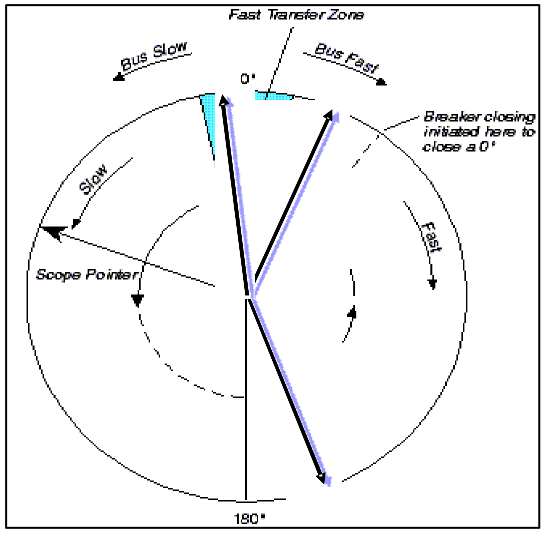

Figure 7 – Fast Transfer

Fast Transfer - Advantages

- High Speed, Fast transfer.
- Transient torques are reduced due to speed of transfer.
- Transfer of complete bus with reduced interruption of process.
- Avoids parallel transfer operation.
- Avoids exposure to breaker failure effects.

4.2.2. In-Phase Transfer

An In-Phase transfer is defined as the method of connecting a motor bus to the new source that have a slip frequency between them, at the first (zero degrees) phase coincidence (the motor bus is coasting down). It is essentially a specialized type of automatic synchronizing under high slip frequency and a rapidly decelerating motor bus frequency. This necessitates the use of very fast measurement and output command techniques. As the slip frequency is changing rapidly due to the deceleration of the motor bus, calculation of the rate of change of frequency may be required in addition to examination of the instantaneous slip frequency when making the new source closing command decision.

The new source breaker will be closed using the In-Phase Transfer Method by predicting movement through zero phase coincidence between the motor bus and the new source during the In-Phase Transfer Enable Window. Closing shall also be supervised by an Upper and Lower Voltage Limit check on the new source and a Slip (DF) Frequency Limit between the motor bus and the new source.

The calculation of the predicted phase coincidence shall be compared with the breaker closing time setting for the new source breaker for the In-Phase Transfer method. In order to accurately predict phase coincidence, considering the decaying motor bus frequency, the phase angle, slip frequency and rate-of-change of frequency between the motor bus and the new source must be calculated and inserted in the second order partial differential equation (Equation 1) to solve for the precise breaker closing advance angle (Φ) to compensate for the breaker closing time (T_B). One cycle response is required by the system.

$$\frac{KT_B\partial^2\Phi}{\partial t^2}+\frac{T_B\,\partial\Phi}{\partial t}+C\Phi=0$$

Equation 1

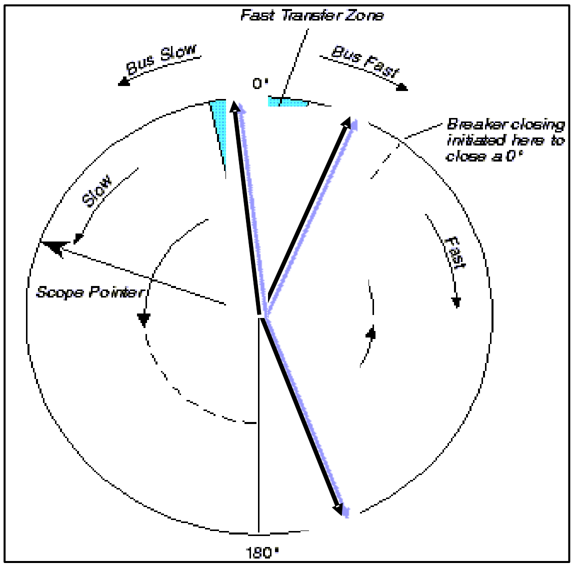

Figure 8 - In-Phase Transfer with advance breaker closing angle

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. The main advantage of the in-phase transfer method is the ability to safely transfer the motor bus to the alternate new 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.

In Phase Transfer - Advantages

- May operate significantly faster than residual voltage transfer.
- Significantly reduces the pre-closure V/Hz due to synchronous closing.
- Permits bus transfer for out-of-synchronism initial conditions or where large initial standing angles prevent fast transfer.
- Provides an excellent backup to fast transfer systems.

4.2.3. Residual Voltage Transfer

In a residual voltage transfer, the motor bus is connected to the new source after the coasting down voltage on the motor bus falls to less than 0.33 pu. In this manner no matter what the phase angle be, the resultant V/Hz will not exceed 1.33 pu. The residual voltage transfer is the slowest one and is not fast enough to maintain process continuity, as certain motor loads that cause rapid stalling may necessitate a restart of the motors on the bus. Also, planned load shedding is quite commonly used before residual voltage transfer. For instance, the large motor loads that slowed down significantly during the coast down will draw large currents upon the transfer of the motor bus to the new source. Such a situation can trigger an over current trip of the new source breaker.

The most important point to be taken into consideration is that the frequency of the coasting down emf of the motor bus also decays gradually and the under voltage permissive element shall be able to measure the voltage accurately at low frequencies. Therefore the set point accuracy of the under voltage elements used for residual voltage transfer at lower frequencies has to be better.

Residual Voltage Transfer - Advantages

- Familiar technique that is widely used.
- Simple to implement with under voltage relays – (but the under voltage elements must operate correctly at low frequencies).

Residual Voltage Transfer - Disadvantages

- Slower
- Process is interrupted due to load shedding (new source cannot re-accelerate all bus motors simultaneously)
- Under voltage relays classically used for residual voltage transfer exhibit set point error at low frequencies that could permit an out-of-phase transfer well above the maximum acceptable resultant V/Hz limit of 1.33pu as per IEEE C50.41-2000 Standard for Bus Transfer.
- Analysis of plant process is required to determine the effects of transfer
- Motor contacts drop out unless designed to stay in at residual transfer voltage.

4.2.4. Fixed Time Transfer

In a fixed time transfer, the motor bus is connected to the new source after the set time delay that would reflect the voltage on the coasting motor bus has fallen to less than 0.33 pu. In this manner no matter what the phase angle, the resultant V/Hz will not exceed 1.33 pu. This type of transfer however will not be able to maintain process continuity, as certain motor loads that cause rapid stalling may necessitate a restart of the motors on the bus.

Fixed Time Transfer - Advantages

- Familiar technique that is widely used
- Simple to implement (time delay relays)

Fixed Time Transfer - Disadvantages

- Slowest
- Process is interrupted due to total loss of power (new source cannot re-accelerate all bus motors simultaneously)
- Analysis of plant process is required to determine effects of transfer (transient torque on motors during restart should be limited to starting torque)

4.2.5. Open Transition - Sequential mode

In Sequential Mode of fast transfer, the old source breaker shall be tripped immediately (<10ms), but closure of the new source breaker shall be attempted only upon confirmation by the breaker status contact that the old source breaker has opened. Upon receipt of this confirmation, all three methods (Fast, In-phase & residual voltage) of transfer can be immediately (<4ms) enabled to supervise the closure of the new source breaker. Closure of the new source breaker will then occur when permitted by the Fast, In-Phase or Residual Voltage

Transfer criteria, whichever occurs first. A typical timing diagram of a Sequential Transfer is shown in Figure 9.

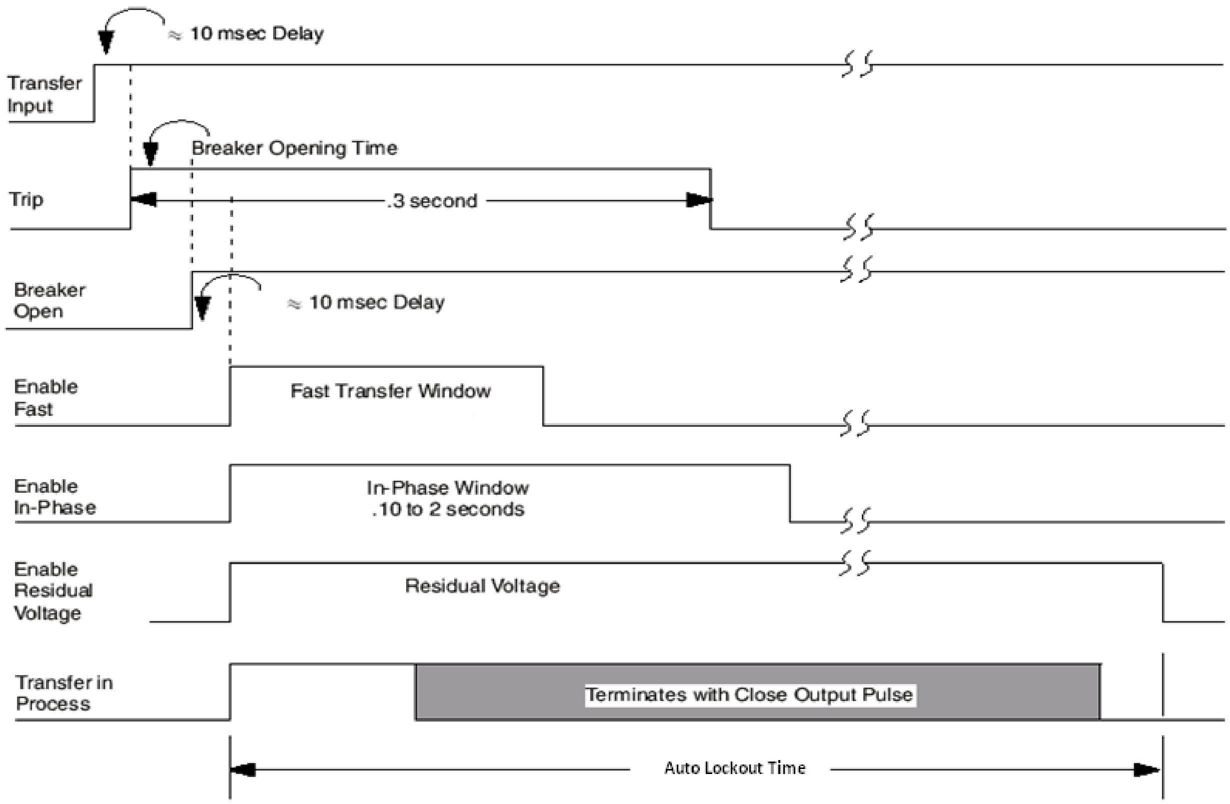

Figure 9 – Time diagram of Open Transition, Sequential Mode

4.2.6. Open Transition - Simultaneous mode

In Simultaneous Mode of fast transfer, all three methods of transfer are immediately enabled (<10ms) to supervise closure of the new source breaker without waiting for the breaker status contact confirmation that the old source breaker has opened. Thus, the commands for the old source breaker to trip and the new source breaker to close could be sent simultaneously, if and only if the phase angle between the motor bus and the new source is within the phase angle limit immediately upon transfer initiation. Otherwise, the old source breaker will be tripped but closure of the new source breaker must wait until permitted by the Fast, In-Phase or Residual Voltage Transfer criteria, whichever occurs first. A typical timing diagram of a Simultaneous Transfer is shown in Figure 10.

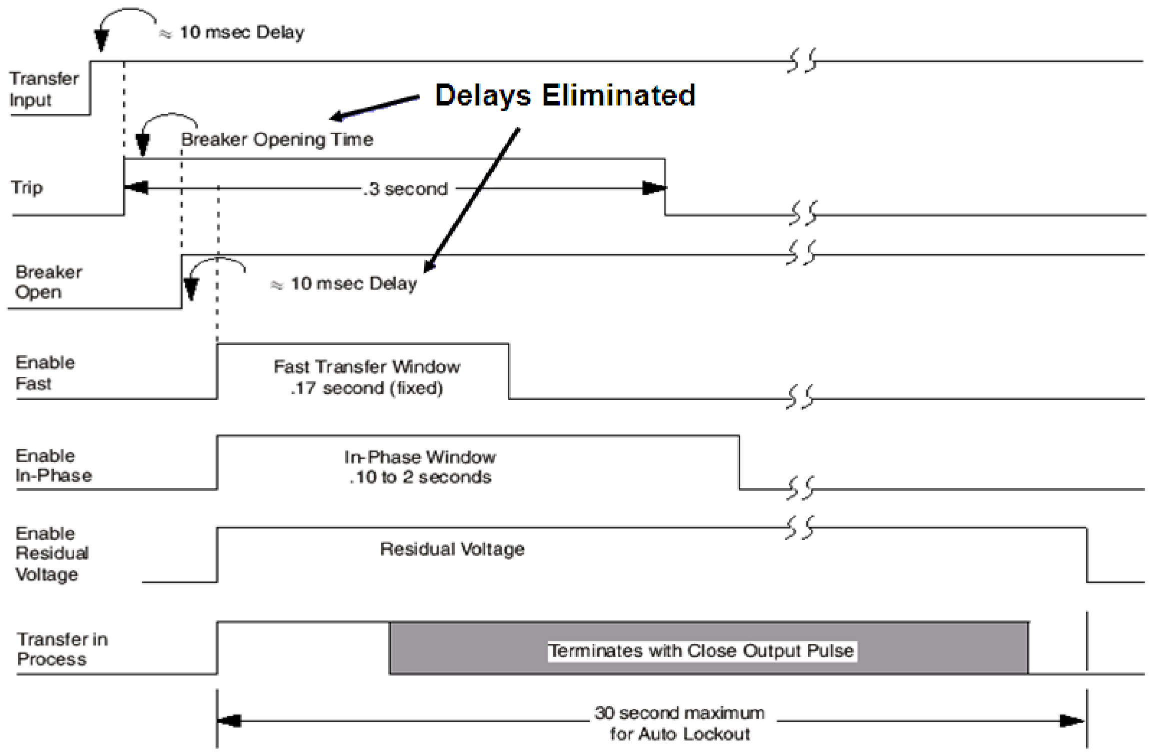

Figure 10 – Time diagram of Open Transition, Simultaneous Mode

4.3. Bus Transfer Initiation

4.3.1. Manual Transfer

Manual transfer is to be initiated from a local human machine interface (HMI), from a control/status Input or through remote serial communications. The manual transfer can allow the transfer operation in either direction from Source-1 to Source-2 and vice versa. Manual Transfer provides Hot parallel transfer or a combination of Open transition Fast, In-phase and Residual voltage transfer. The Manual Transfer will be blocked when any Lockout/Blocking condition occurs. The High Speed Motor Bus Transfer System will not respond to any transfer command while in Lockout/Blocking condition.

4.3.2. Automatic Transfer

Automatic Transfer can be initiated by a protection signal viz. trip signal (86) or an under voltage function (27) or triggered by a sudden loss of motor bus supply voltage (27B Function) or frequency based tripping. Auto transfer allows the transfer operation in either direction from Source-1 to Source-2 and vice versa. Auto Transfer provides Open transition Fast, In-phase, Residual voltage and Fixed time transfers. The Auto Transfer will be blocked when any Lockout/Blocking condition occurs. The High Speed Motor Bus Transfer System will not respond to any transfer command while in Lockout/Blocking condition.

5. Conclusion

- The Fast Transfer synchronizes a motor bus within few cycles practically without losing any loads thus maintaining the process continuity and improves the life expectancy of the motors with safe and reliable source transfers. The sync check equipment that is used for supervising fast transfers must be able to detect a phase angle pickup or block very rapidly if the angle moves in or out of the desired range.
- The in-phase transfer offers an opportunity to synchronize a motor bus on the first available slip cycle. This type of transfer will enable process continuity as the motors are still spinning and the resultant V/Hz for an in-phase close is well below the 1.33 pu maximum.
- The power frequency under voltage relays classically used for residual voltage transfer exhibit set point error at low frequencies that could permit an out-of-phase transfer well above the maximum acceptable resultant V/Hz of 1.33 pu as per IEEE Standard C50.41-2000. Therefore the Bus Transfer Schemes with classical under voltage relays is not adequate and hence the need for a special Bus transfer device.

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