ENVIRONMENTAL SUSTAINABILITY WITH SYNCHRONOUS TRANSFER ON MEDIUM VOLTAGE DRIVES

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Abstract – A variable frequency drive (VFD) is a versatile piece of equipment which must be designed to suit a wide range of industries, applications, and power systems. One such application is for the VFD to perform a Synchronous Transfer of the motor from a variable frequency bus to fixed frequency bus and back. It allows multi-motor systems to operate between fixed and variable speeds, as required by the process. Synchronous Transfer control on Medium Voltage Drives (2.3kV-13.8kV). allows operation of the motors in a sustainable manner with allowing the motors to run at the optimal speed requirements demanded by the process thereby operating efficiently. This paper reviews how a Synchronous Transfer scheme may be applied on different drive topologies. It will include Voltage source inverters (VSI) and Pulse Width Modulated Current source inverters (PWMCSI) operating induction or synchronous motors with open or closed transitions. with the objective of maximizing operational efficiency. The synchronous transfer control technologies may be in combination of embedded firmware control in the drives or with external discrete synchronizing relays. With a Programable Logic Controller (PLC) in the drive control system the customer can interface to their control system remotely or locally through an Human Machine Interface (HMI) at the drive control panel. Additionally, the HMI provides a back-up mechanism for service and diagnostics.

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Index Terms — Medium Voltage Variable Frequency Drive (VFD), Variable frequency drive (VFD), MV motor control, Synchronous Transfer, Heavy Industry applications, Bus Transfer, Open Transfer, Closed Transfer

I. INTRODUCTION

Variable speed drives provide numerous application benefits. The benefit of energy savings alone will convince many users to implement drive technology. Energy saving principles and energy saving studies associated with medium voltage drives are well documented in [1] - [3]. Efficiency of different medium voltage topologies is also well researched and documented [7]. However, application of Medium Voltage Variable frequency drives (VFD) for maximizing system operational efficiency and flexibility, using Synchronous transfer on multi-motor system control shown in Figure 1, is not well documented. This paper presents application use cases for synchronous transfer control technology applied to Medium Voltage PWMCSI or VSI, with the objective to maximize energy savings. There are several options for system control to allow the user to customize to their unique application requirements and integration into the overall control philosophy . The flexibility of applying synchronous transfer control on VFD applications has a direct impact on environmental sustainability through energy savings.

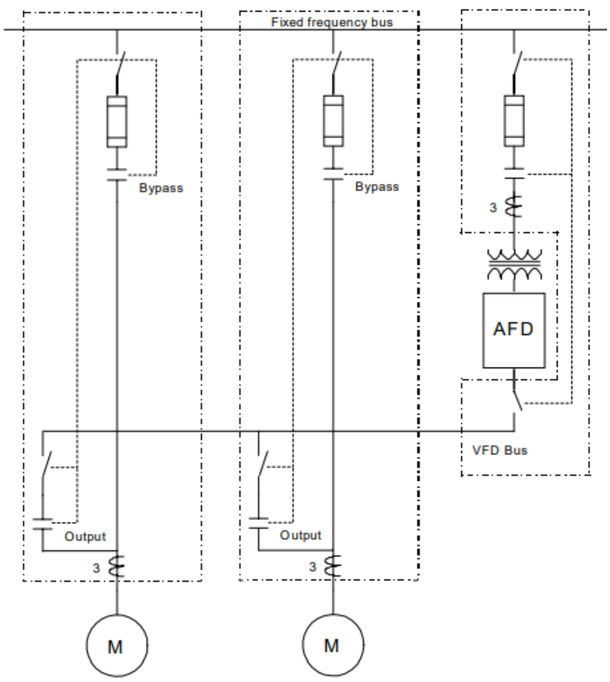


Figure 1 – Typical Configuration of a Two motor Synchronous Transfer System

II. SYNCHRONOUS TRANSFER PRINCIPLES

Motor Bus Transfer (MBT) is used in industrial applications to achieve process continuity in the event of a power outage or when transferring the motor from one bus to another. The MBT is discussed in [4] with definitions provided to characterize the different types of MBT. Generally, the four categories are:

1. Hot Transfer
2. Open Transfer
3. In Phase Transfer
4. Residual Transfer

These categories provide a common terminology when discussing this concept in industrial applications. The scenarios on which these categories apply consider that the VFD would apply to the motor stator rated bus frequency typically 50Hz or 60Hz .The rotor will be operating at a slightly lower speed, slip frequency. To accomplish a transfer, the motor is first de-energized, then based on a pre-set time the incoming power is re-applied to the stator. The duration of the pre-set time is what defines the MBT category as shown in the table 1.

IEEE Bus Transfer Classification	Time Interval to Restore Power	VFD Classification
Hot	0	Closed
Open (Fast)	<5 cycles	Open
In Phase	<20 cycles	Open
Residual	<2 seconds	Open

Table 1. Motor Bus Transfer Classification

When discussing MBT in a VFD application, the terminology used is Synchronous Transfer. Synchronous transfer is defined as the ability to transfer a motor from a VFD to a fixed frequency supply (Synch) or the ability to transfer a motor running on fixed frequency supply to the VFD (De-synch). This transfer can be done entirely using a commercially available Synchronizing relay and a system PLC or could be done with software embedded within the VFD firmware along with a system PLC.

The key difference between the MBT and Synchronous Transfer is the ability of the VFD to accelerate the motor above synchronous speed prior to de-energizing the motor. An advantage of running the motor above synchronous speed is to place the motor voltage leading the fixed bus voltage. Once the synchronous controller has obtained the desirable lead angle, it commands the VFD to stop. The motor will then start to freewheel accompanied with a decay in the motor terminal voltage and frequency. After a certain measured time interval, the motor voltage will have lagged sufficiently to now be in phase with the bus voltage. It is at this moment the power poles of the bypass contactor close with near perfect synchronizing. In MBT the motor voltage starts out lagging and will continue to lag, perfect synchronization is not easily obtained.

This concept of synchronous transfer with a VFD has two general classifications of Open and Closed transition. As described above, for a very short period (1-3 electrical cycles) the motor will be de-energized, as shown in Figure 2. This aligns with the concept of Open Transfer as defined in MBT terminology. While it is classified as an Open Transfer, it is an Open Transfer that is completed with the motor voltage in phase with the incoming bus voltage; it may be considered an “Enhanced Open Transfer”. This significantly reduces inrush current and the transient torque when compared to the traditional Open Transfer without a VFD.

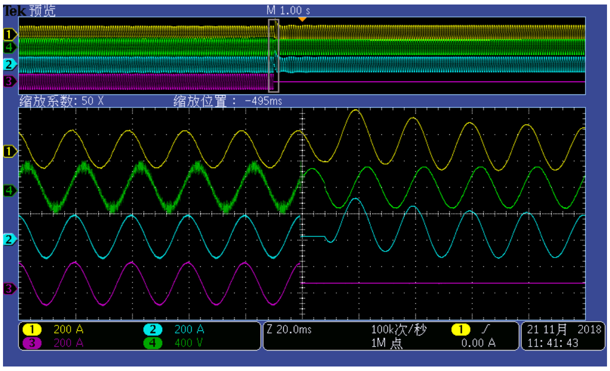


Figure 2 – Open Transfer with VFD

The second possibility, closed transition, the VFD is to have both the motor and VFD energized at the same time for a short period, then de-energizing the VFD. The VFD will synchronize its output voltage with the incoming voltage source. In this case, there is no lead angle required. Once the two voltage sources are synchronized, the incoming source is connected in parallel with the VFD . After a very short period, the VFD is de-energized, leaving the motor to run directly on the utility feed. In this scenario, the motor does not see an interruption of electrical energy. This is called Closed Transfer with the VFD, Figure 3. This solution requires a Reactor on the output of the VFD to limit current flow from the power system into the VFD output converter

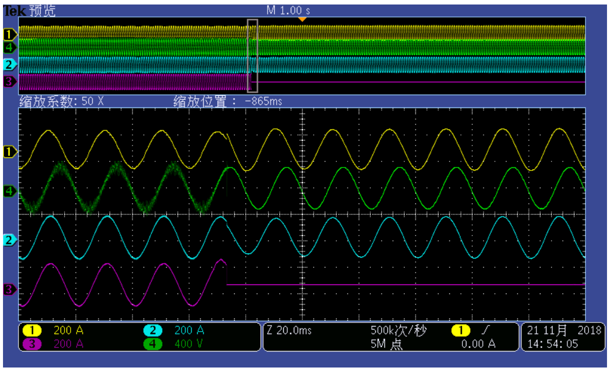


Figure 3 – Closed Transfer with VFD

The two most common topologies in Medium Voltage VFD are the VSI and PWMCSI When comparing these two topologies for the synchronous transfer application both exhibit similar features and a few differences. They both can be used with a synchronous regulator to provide a lead angle for the case of Open transfer and also to lock into the bypass utility source in case of Closed transfer.

For an open transfer, the period when the motor is de-energized and waiting for the bypass source to be applied to the stator, the VSI topology does not have a means to support the motor rotor flux as it decays. The rotor flux will decay rapidly based on its open circuit time constant. For the CSIPWM topology, its inherent Motor Filter Capacitor (MFC) will support the rotor flux as the motor inductance and MFC exchange energy. In this case, the motor terminal voltage remains near constant for a window that can reach 5 cycles. The actual transfer will occur optimally near the 2nd cycle.

One additional benefit from the CSIPWM solution is to leave the MFC connected to the motor; it effectively becomes a power factor correction capacitor for the motor.

The VSI does not have a MFC on its output terminals. That can be an advantage by allowing the VFD to be immediately turned off and not have any energy source connected to the motor. This allows for the VFD to be stopped and the motor can be re-connected to the bypass almost instantly, within 1 electrical cycle. While the PWMCSI can be immediately stopped, the MFC and motor inductance transient response requires approximately two cycles to decay. Thus, the transfer is not performed in these first two cycles for the PWMCSI VFD.

The Closed transfer scheme works equally well for both the VSI and CSIPWM topology. The VFD will be connected in parallel with the utility source for a very brief interval (1-2 electrical cycles). An output reactor on the VFD output is required to account for this case where the utility feed is connected directly to the VFD output. While they are synchronized, any slight asynchronous behavior will result in back feeding into the VFD from the utility source and possibly damaging the VFD. The output reactor limits this back feed of energy and allows the VFD to be quickly de-energized.

The synchronous transfer application with a VFD can be applied to both Induction and Synchronous motors. For the case of Synchronous motors, the exciter control must be accounted for in the design. While the motor is controlled by the VFD the exciter must be controlled by the VFD. When the motor is transferred to bypass, the exciter control can remain under VFD control. In most cases, the exciter control is also relinquished to an external controller to allow the VFD to be completed de-energized.

III. CONTROL SYSTEM DESCRIPTION

The basic principle of a synchronizing function is to find the instant when the VFD output voltage and the incoming bus voltage to which the motor will be transferred are in synchronism. This means that the phase sequence is the same and the frequency, magnitude and phase angle of the two voltages are within permissible limits. This is accomplished by using voltage feedback signals from both sources then processing them in real time. The control loop is a closed loop adjustment of output voltage magnitude(δ_V) and output frequency(δ_f) to ensure that the two measured voltages are in synchronism for a certain time period allowing a smooth transfer by opening CB1 and closing CB2 (Figure 4). The synchronizing control system can be a standard P (Proportional) or PI (Proportional-Integral) controller in which the error in the Phase Lock Loop angle between the bypass source and the drive output, results in fine adjustment of the drive operating frequency so that the error is driven close to 0 (typically a maximum of ± 3 degrees.). The controller bandwidth should be lower than the rate at which the drive control system can change the output frequency ensuring stability of the system.

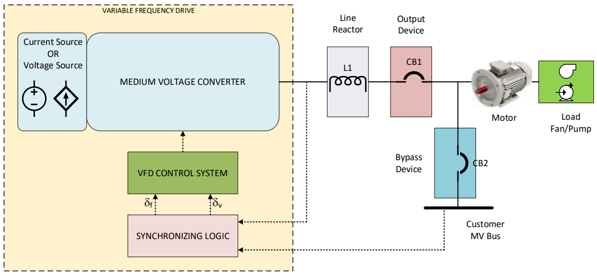


Figure 4 VFD based Synchronous transfer

De-synch procedure is the reversal of Sync in which after synchronism is achieved, VFD opens CB2 and closes CB1 thus allowing VFD to control the motor.

The transfer in either direction can be realized in two ways: Close or Open Transfer. As shown in Figure 5,

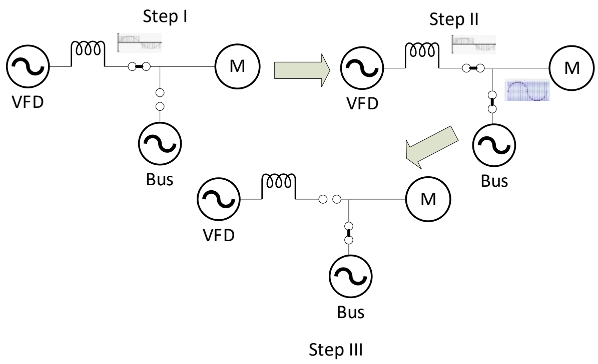


Figure 5 Close Sync Transfer (Motor to Bypass)

In Open transition an intentional delay (~1 line frequency cycle) is added such that at the moment of transfer the VFD is completely OFF. For an open transfer a line reactor is not required. Both Open or Closed transfer is applied with either CSI or VSI based VFD topologies. The choice for selection of Open or Closed is matter of customer preference. From our experience, an application consideration influencing the selection is the allowable speed droop for the process.

IV. SYNCHRONOUS TRANSFER SYSTEM CONTROL

Synchronous Transfer System Control is achieved using Programmable Automation/Logic Controllers (PACs/PLCs). The primary function of the PLC is to be a marshalling (central connection) and control point for all system equipment. Typical functions that a programmable controller performs in a synchronous transfer system include:

A. Power System Consideration
B. Equipment Interface Flexibility
C. Physical Component settings/adjustment
D. System Interlocking and Control Logic
E. Control System Fault Tolerance
F. Application Control Requirements
G. Field Excitation Control (synchronous motors)

H. Local System Control and Visualization

A. Power System Consideration

A synchronous transfer system may be as small as a single VFD, motor, with Output/Bypass switching devices or the system could contain multiple VFD's, motors, output/bypass and bus tie switching devices. The PAC/PLC connects all devices in the system to a central control point. It can be scaled to suit the size requirements of the system.

B. Equipment Interface Flexibility

Switchgear, VFDs, Motor Protection relays, and External Control Systems (PLCs, DCS, etc) are all components that are typically a part of a Synchronous Transfer system. These components are commercially available from numerous vendors, and as such may have varying hardwired and network interface requirements. A PAC/PLC provides the means to bridge all equipment together onto a common platform. Typical interface requirements for the components are as follows:

1) *VFD:* Most of the interface is networked while critical signals (e-stop, switchgear command and status, etc.) remain hardwired.
2) *Switchgear:* All critical timing signals (close/open commands and emergency shutdown) are hardwired while remaining signals may be connected to networked (remote) I/O to reduce the use of wire and material
3) *Protection/Synchronization Relay:* Any protection trip and switchgear open/close signals are hardwired while the remainder may be connected to networked I/O or the relay network port
4) *External Control System:* This can vary widely, however with exception of emergency shutdown, the entire interface may be networked or hardwired. The number of control system devices connected to the Synchronous Transfer controller depends on site philosophy; there may be one central control system each piece of equipment may have an individual controller.

C. Physical Component Settings/Adjustment

Whether intentional or not, motors and switchgear in a Synchronous Transfer system may not possess identical physical characteristics with respect to each other and the Synchronizing device (VFD or relay) may require different parameter settings depending on the motor and switchgear to be operated. The Programmable Controller can be programmed to manage these differences.

1) *Motors:* Motors with different nameplate ratings may be used in the system, with the VFD designed to operate at this range of ratings. Application code in the controller can be written such that the correct motor data is set in the VFD prior to its operation of the motor. These values are stored in either controller or VFD memory.
2) *Switchgear:* Regardless of switching device type (contactor or circuit breaker) used, the possibility exists that closing and opening times can vary between different output/bypass device pairings. These switching times are measured and placed into controller memory, and the programmable controller sets the required values/parameters in the synchronizing device (VFD or relay) controlling the switching during a Synchronous Transfer event.

D. System interlocking and control logic

Application code within the PAC/PLC is written such that interlocking permits only one motor and VFD to be connected to any segment of the VFD output bus at any given time. When bus tie switches are open in a system, the logic is written to permit each drive to be controlling a motor simultaneously on separate VFD output bus segments.

E. Control System Fault Tolerance

Synchronous Transfer Systems are regularly connected to large processes and high value equipment. Failure of the motor control system can result in major process disruptions and/ costly downtime for the equipment owner. Steps can be taken with the control system to tolerate faults and continue to operate. Examples of fault tolerance include:

1) *Controller Redundancy:* PAC/PLC vendors have redundant processor products capable of operating in parallel such that if one fails the other continues with operation and no interruption results.
2) *Network Redundancy:* Network topologies (ie. Ring) and protocols (ie. Parallel Resiliency Protocol) can be implemented in a system to tolerate a lost network connection or failed component.
3) *Power System Redundancy:* Additional power components, such as VFDs and switchgear may be incorporated into a system to provide a backup means of operating should the unit (VFD) in service fail. When designed correctly it is possible to isolate and service a faulted unit while running, thereby improving the system sustainability.

F. Application Control Requirements

It is widely understood in industry how versatile PAC/PLCs are. This is the largest advantage of their use in Synchronous transfer systems. They can be programmed to suit any number of Application Control requirements without making any physical changes to the power hardware used in a Synchronous transfer system. Examples of Application Control requirements include:

1) *Soft Starting:* The PAC/PLC is used to start a motor and automatically transfer (bypass) it to the AC line. The result is a reduction of impact to the power system due to the elimination of a high inrush current compared to across-the-line motor starting.
2) *Across-The-Line Motor Starting:* Because the PAC/PLC can control each bypass switching device, across-the-line motor starting is a backup means available should the VFD be unavailable.
3) *Redundant Drive:* Some power systems require a VFD only as across-the-line starting is not an acceptable method of starting. In such cases additional drives may be added and included in the PAC/PLC such with application code selecting the VFD available for use.

   4) Control Interface: Site control systems may require network connections, hardwired connections, and interface to multiple systems. Multiple vendor PAC/PLCs provide the ability to adapt to these conditions while the Synchronous

Transfer power hardware does not change, making the design more sustainable. Fig. 6 outlines the typical parts of a Control System, with the site control interface located between the System Controller and the Drive PLC.

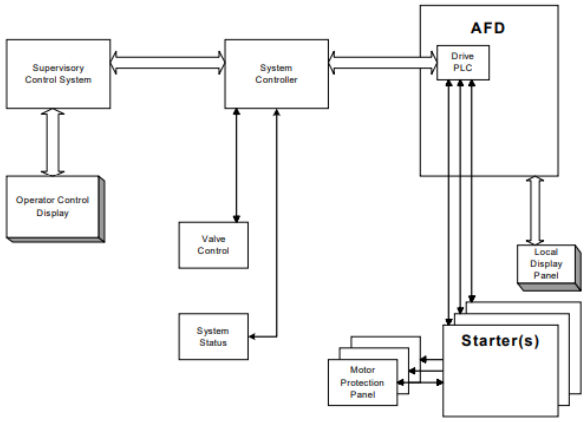


Fig. 6 – Control Block Diagram for Synchronous Transfer System

5) *Process Consideration:* The process that the Synchronous Transfer system is connected to may require adjustment of motor speed (by use of VFD) to control a process variable such as pressure, flow, or level. It is possible to program control of this process variable in the PAC/PLC along with automatically synchronizing (or de-synchronizing) motors as required by the process.

6) *External Protection:* Depending on the location/industry the Synchronous Transfer system is utilized in; external protection devices may be required as part of the system. A prime example of this is the requirement in the Water/Wastewater industry for vibration and temperature monitoring. A PAC/PLC provides a suitable means to incorporate this.

7) *Power Factor Correction & Control:* When motors are bypassed it may be desired to energize power factor correction capacitors to compensate for lagging power factor. When control of capacitor banks is connected to the PAC/PLC they can be programmed to bring these capacitors online/offline.

G. Field Excitation Control (Synchronous Motors)

Motors to be controlled in system may be of synchronous construction and have a separate field excitation package to be used with their operation. A VFD would be required to control this package when connected to each motor, yet it would not be able to control this when the motor is running on bypass. A programmable controller provides the means to select which field exciter is to be controlled by the VFD, and to provide a field current reference/source when the motor is running on bypass. It is common for synchronous motors in these systems to have their bypass field current reference set for site power factor compensation.

H. Local System Control & Visualization

With all equipment connected to a common control system it is possible, and greatly beneficial, to have a Human Machine Interface (HMI) terminal for local control and to view the state of the equipment.

1) *Local Control Screen:* This provides a method to control each motor within the synchronous transfer system. An example screen is shown in Fig. 7. Note that normal method of control is from the System Controller and local control is a backup method for service and operators when required.

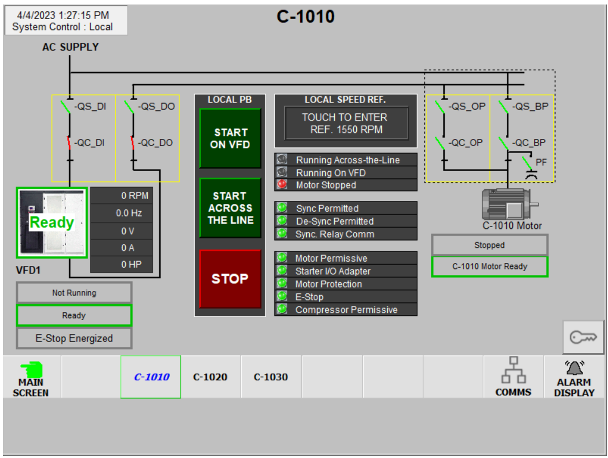


Fig. 7 – Motor Local Control HMI screen

2) *System Overview Screen:* This provides a method for a user to view the state of equipment in operation as shown in Fig. 8.

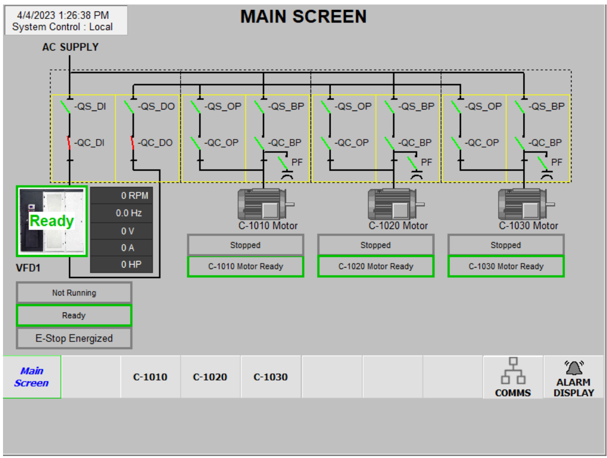


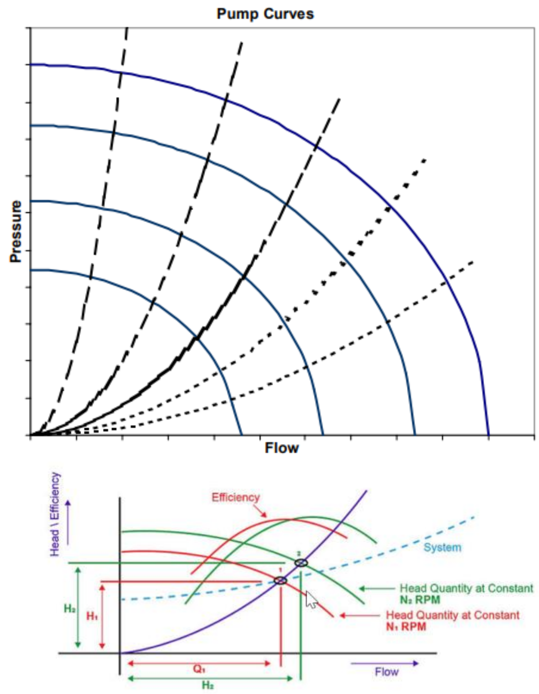
Fig. 8– System Overview HMI screen

V. Application Use Cases

Today, savings in energy costs and optimizing the processes for energy efficiency offer the single largest opportunity for companies to drive action towards meeting their sustainability goals. The Sustainable Development Goals Report 2022 from United Nations mentions that Improving energy efficiency is fundamental to meeting global climate goals. The target for global energy efficiency remains within reach, but only with significant investment on a systematic scale.

This section discusses various implementation schemes for Synchronous Transfer on Medium Voltage Drives supporting goals of energy efficiency and maximizing asset utilization.

Advantages of applying variable frequency drives for energy savings are well understood and documented. Typical variable torque applications operating with varying speed, following the Affinity Laws, present a strong economic justification based on energy savings to replace a mechanical throttle device such as a damper on a fan or a throttle valve on a pump with a variable frequency drive to regulate the flow and speed. Refer to Fig. 9 for Affinity Laws. A nine month to two-year payback period is typical when Medium Voltage VFDs are applied to control the output of a pumping system instead of throttling with control valves [5]. In addition to motor control and energy savings, a VFD contributes to optimizing the control of the overall application process.



$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \qquad \frac{H_1}{H_2} = \frac{N_1^2}{N_2^2} \qquad \frac{BHP_1}{BHP_2} = \frac{N_1^3}{N_2^3}$$

Fig. 9 – Affinity Laws applied to a Pump -Constant efficiency lines (dotted) with variable speed pump curves (solid)

Synchronous transfer i.e., ability to transfer back and forth the power source of the motor between a variable supply (drive) and a fixed supply (AC utility power line), can be implemented in a wide range in the electrical schemes for the overall plant / process control. Additionally, there is ability to handle the control of other auxiliary devices and functions within a system. These schemes can be implemented with no to minimal interruption of power for same or different motor ratings. The System lineup may have motors with different ratings, and/or power system fed from single or multiple sources. With added layers of redundancy in control and equipment hardware, these schemes provide energy savings, optimizing the process, contributing to sustainability goals of the project.

A detailed review of some of these schemes is presented, starting with basic building block with a stand-alone single motor synchronous transfer system (Fig. 10). This scheme can be expanded to multiple motor operation and control (Fig. 11)

Fig. 10 and 11 are single line diagrams of a motor output-bypass starter and an overall single line diagram of single motor synchronous transfer system respectively.

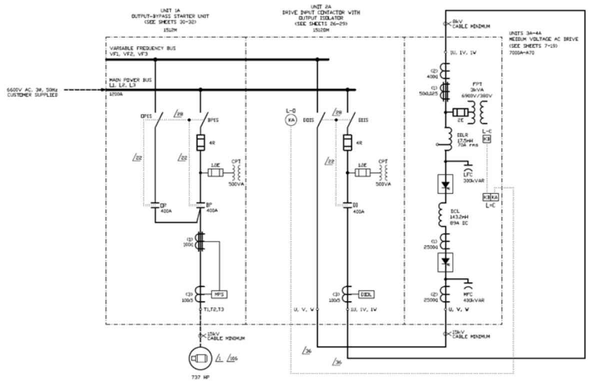


Fig. 10 - Single Motor Synchronous Transfer System Single Line Diagram

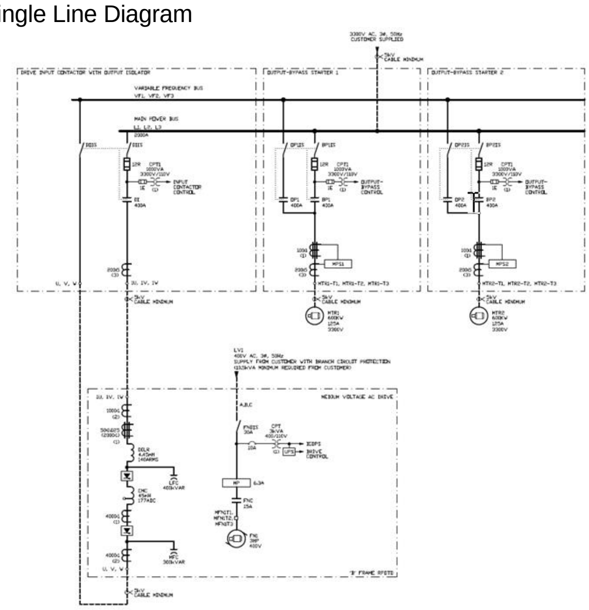


Fig. 11- Two Motor Synchronous Transfer System Single Line Diagram

Note that the output (OP) contactor connects the motor to the variable frequency supply (drive) and that the bypass (BP) contactor connects the motor to the fixed frequency power supply.

These applications especially on pumps or compressors - example Municipal pumping station for Water / Wastewater or Natural Gas pipeline for Oil & Gas are designed for continuous production and operation due to the constant demand required from them and high availability. Not all motors need to be on-line and require speed control. In applications like this, it is desirable to have a drive system with synchronous transfer control on multiple motors, keeping the number of drives to a minimum, thereby keeping the project cost down. With the Variable Frequency Drive (VFD) starting up the motors limiting the inrush current and sequentially transferring those that need to run at full speed/load to power line bus for Direct-on-Line (DOL) operation allows increased uptime with no process interruption.

With synchronous transfer control a drive may be applied for soft start duty only i.e., the application is used to start motor(s), accelerate to full speed and transfer to the bypass source. The drive is not intended for continuous application. Therefore, the ampacity rating of the drive can be reduced to match the starting requirement for the load. The drive is not rated for the motor horsepower rating, only the starting horsepower requirement. This means more economically appropriate selection of the drive is made, not only resulting in lower equipment hardware costs, but added benefits of lower integration costs (smaller footprint etc.)

In the above use cases, the longevity of the drives is prolonged as the asset is optimal used, thereby requiring less maintenance and spares over the life cycle. Overall system efficiency and energy savings is achieved by removing, or not requiring, use or maintenance of certain apparatuses, contributing to the goal of operating the facility in a sustainable manner.

A field retrofit may be applied to an existing Variable frequency Drive (VFD) operated motor if it is determined that the application process cycle requires the motor to runs at full load / full speed for sustained periods while still requiring the VFD to provide speed control flexibility and starting capability. For example, minimizing utility disturbances during motor startup on a weak power system. Applying a field retrofit on existing VFD operated motors with a Bypass / Output controller will balance operational demand between VFD control and Direct-on-Line (DOL) operation and result in energy savings. Energy loss through the drive is eliminated for the duration the application is on DOL. Example a 1000 HP, 4160V MV motor with a typical efficiency of 95% and 0.85 power factor if required to operate at full load speed for more than 2.6hrs will save 38kVA of energy if transferred across the line through synchronous transfer by an MV drive with typical efficiency of 96%.

Today many customer installations may require a mix of power supply sources including renewable power to efficiently manage and balance their cost of energy. In such applications flexibility to switch between optimal power source depending on the time of the day matched to the operational requirements is a requirement. Synchronous Transfer scheme may be adapted to integrate more than one power source. Fig. 12 outlines a scheme for a customer with 2 independent power sources for a 6-motor synchronous transfer system. This feature is made possible sectionalizing the out-bypass controllers matched to the number of input power sources.

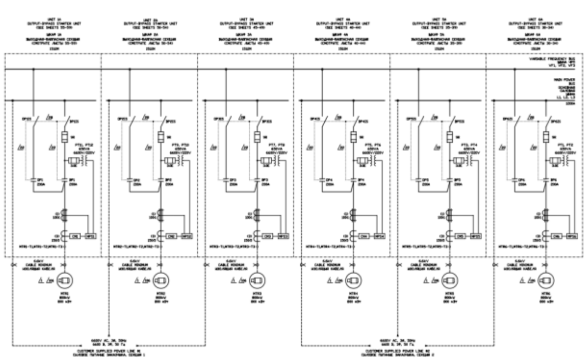
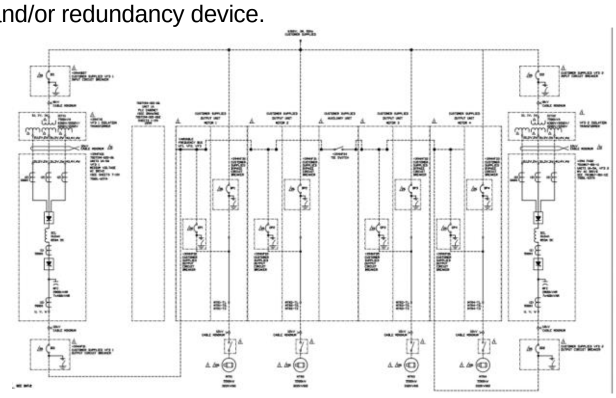


Fig. 12 – Six Motor Synchronous Transfer System Single Line Diagram with two independent power sources

To meet goals of maximum operational flexibility and redundancy for high availability, a Synchronous Transfer system may be offered with redundant VFDs with or without a tie switch arrangement that offers ability to control motors from any one drive. This means that the standby drive is required with ability to operate the same motors that the faulted drive previously had control of. Further, with PLC integrated into the control scheme, the system may be configured to use switchgear (circuit breaker) output / by-pass cabinets instead of motor controllers. Also, with design flexibility from PLC the output/by-pass controllers may be procured under contract for switchgear, separately from VFDs, optimizing lowest total cost of procurement. Another variant to optimize hardware costs may be to use a reduced voltage soft starter instead of a VFD, as back up and/or redundancy device.



Fig, 13 – Redundant Variable Frequency Drive Synchronous Transfer System with tie switch

Another variant of redundant drive system configuration is shown in Fig. 14. In such cases, a PLC is normally placed in a separate enclosure such that if either drive is shut down to be serviced, the PLC and necessary control power will remain energized for the backup (or reserve) drive to be brought into service on short notice.

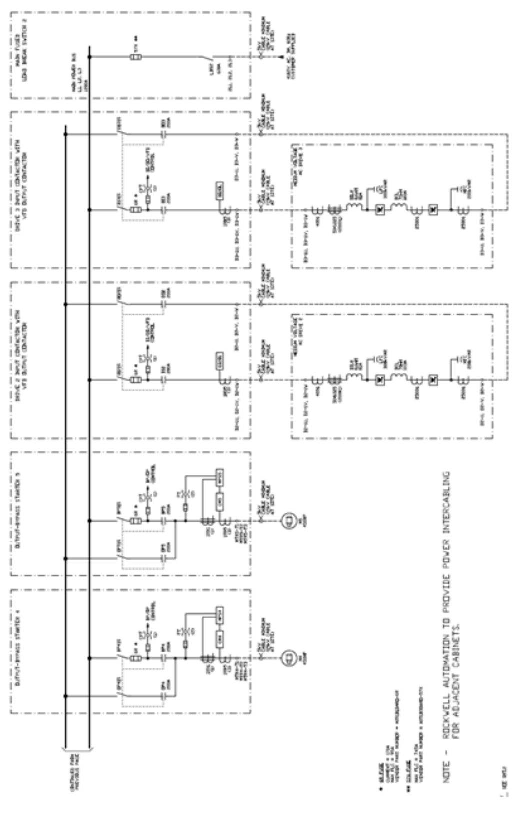


Fig. 14 - Redundant Drive Scheme Single Line Diagram without tie switch

VI. CONCLUSIONS

A modern flexible synchronous transfer control for Medium Voltage Drives in a multi-motor control system can be very beneficial from process or economic standpoints. Along with reduced initial capital outlay and installation costs, savings can also be realized in operating costs since the process is now continuously variable and does not require throttling resulting in energy savings. The VFD will provide improved process control as well as the benefit of soft starts and reduced voltage drops. There is flexibility in how the transition (synchronizing and desynchronizing) may be implemented via embedded S/W or through external devices to provide accurate phase alignment at the moment of connection to the second source. Minimizing the voltage phase difference will reduce current and torque transients important to providing a long motor life. This range in design options for synchronous transfer motor control offer choices to customers to tailor the implementation scheme(s) to their unique operational needs, conserving project costs, energy usage, maximizing asset utilization and life, allowing environmentally sustainable project development.

VII. ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution of Carlos Siri for providing field data from actual commissioning of synchronous transfer systems.

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