Fundamentals of Main Tie Main schemes and state machines

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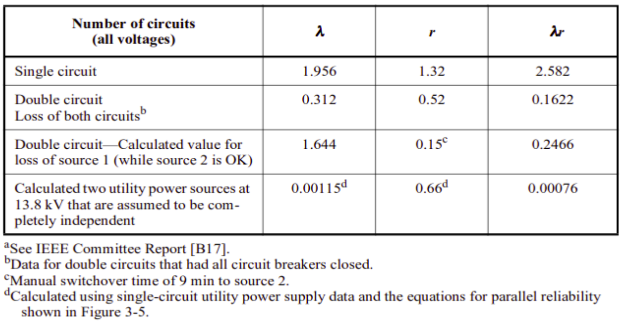
***Abstract*— Often large facilities have processes that can justify the added expense of having a redundant source and a means to transfer load without interrupting the process. This paper reviews the fundamentals of main tie main schemes, methods of transferring load (fast, in-phase, and residual/fixed time) and how state machines can be used to make the relay logic more readable and easier to troubleshoot.**

Keywords— main tie main, motor bus transfer, fast transfer, in-phase transfer, residual, finite state machines

I. INTRODUCTION

There are many industrial facilities that have high cost associated with plant interruptions. At refineries and chemical facilities, an interruption in the process can require flaring and purging the process after an interruption and involve a long restart process. The cost associated with this is not just in wasted chemical feedstock but also lost production. Facilities like these can justify having a redundant connection to the grid. Often these facilities are fed by two independent electrical sources. A common arrangement to make use of the two independent connections to the grid is a main tie main arrangement. This setup can be used to transfer load from one source to the other for planned and emergency transfers.

The potential improvements in reducing outage frequency and improving availability can be see in Fig 1. **λ** is the source failure rate per a year and ***r*** is average time to repair in hours. The frequency in loss of utility service and unavailability **(λ*r*)** is typically reduced by over 99% when a facility goes from a single connection to the grid to two independent sources with an automatic transfer scheme that can transfer load in less than 5 seconds.



Number of circuits (all voltages)	λ	r	λr
Single circuit	1.956	1.32	2.582
Double circuit Loss of both circuits[b]	0.312	0.52	0.1622
Double circuit—Calculated value for loss of source 1 (while source 2 is OK)	1.644	0.15[c]	0.2466
Calculated two utility power sources at 13.8 kV that are assumed to be completely independent	0.00115[d]	0.66[d]	0.00076

[a] See IEEE Committee Report [B17].
[b] Data for double circuits that had all circuit breakers closed.
[c] Manual switchover time of 9 min to source 2.
[d] Calculated using single-circuit utility power supply data and the equations for parallel reliability shown in Figure 3-5.

Fig 1. IEEE survey of reliability of electrical utility power supplies to industrial plants. [1]

II. MAIN TIE MAIN ARRANGEMENT

A. *Arrangement*

The main tie main arrangement common among industrial facilities utilizes two sources. There are three breakers in the arrangement, one breaker for each main and usually one tie breaker. Two tie breakers are sometimes used to completely isolate two sections of switchgear for maintenance. The tie breaker is usually open and used to transfer load from one source to the other.

B. *Devices and connections*

The scheme can be controlled by one device if it has enough inputs. Often, two or three devices are used to automate the transfer scheme and have other duties besides automating the transfer scheme like relay protection or breaker failure.

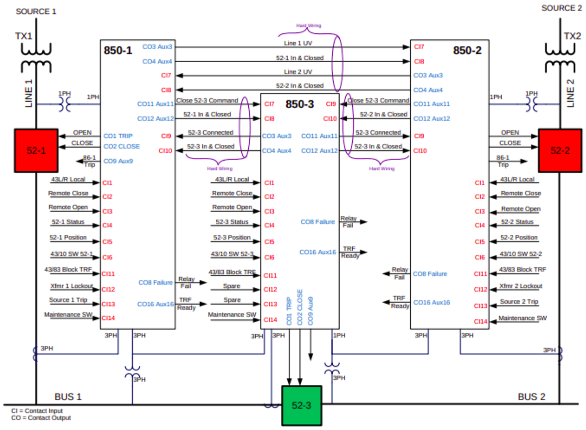


Figure 1. MTM Transfer Scheme Layout

Fig 2.

Fig.2. Typical main tie main arrangement hardwired with GE 850 relays. [2]

C. *Modes of operation*

There are no firm rules as to how a main tie main scheme should operate but often they have a few very common traits.

C.1 Automatic Transfers

Automatic Transfers are the heart of the main-tie-main scheme. Automatic transfers are usually initiated when the system is in its normal state (two main breakers closed and the tie breaker open) and unhealthy voltage is detected on one of the sources (27 relay) or one of the mains is lost due to a protective trip. This initiates a transfer from the unhealthy bus to the healthy bus.

C.2 Automatic Re-Transfer

Automatic re-transfer is sometimes included to handle the transferring of load to its original source after an automatic transfer. If the unhealthy voltage returns to healthy for a specified amount of time, that main breaker closes if synchronized and the tie breaker opens after a delay. This returns the scheme back to its original state.

C.3 Live Source Seeking Logic

In the event that both sources are lost at the same time ,which can happen if both sources are not truly independent, the logic can open the two main breakers. If both sources return at the same time, then both main breakers will close. If one source returns, that main breaker will close and the tie breaker will transfer over the other bus's load. When the other unhealthy source returns, the other bus's load will be re-transferred back to its own source.

III. SYNCHRONOUS TRANSFER

Industrial power systems tend to be loaded heavily with motors. When industrial loads are transferred from one bus to another, it must be done in such a way that the motors are not unduly interrupted or damaged. A transfer that can to happen without creating excessive torques or interrupt the process is considered a synchronous transfer.

A synchronous transfer of an induction motor is defined by as not exceeding 1.33 pu V/Hz at the time of the transfer, closing the tie breaker. [6] This 1.33 V/Hz quantity is not correlated directly to torque but is a heuristic that electrical engineers use to define a safe transfer.

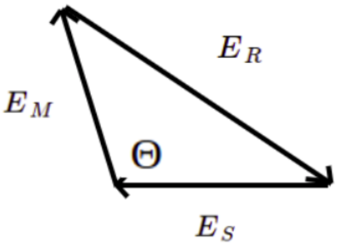


Fig. 3. Vector Diagram showing how to calculate volts per hertz calculation [3]

In this vector based calculation:

$$E_M = V_{motor} / Freq_{motor} \quad \text{(motor bus in P.U.)}$$
$$E_S = V_{source} / Freq_{source} \quad \text{(new source bus in P.U.)}$$
$$E_R = V_{resultant} / Freq_{resultant} \quad \text{(V/Hz at the time of transfer)}$$

Θ = Angle difference between motor bus and new source at time of transfer

$$E_R = \sqrt{E_S^2 + E_M^2 - 2E_S E_M \cos(\Theta)}$$

Under normal conditions, both E_M and E_S will be close to 1 P.U with both their voltages and frequency being very close to nominal. There may be standing Θ angle difference between the motor bus and the new source under normal conditions. This angle difference might be the result of an angle difference between the two source connections, loading, or by having different transformer connections. This standing angle difference will have an impact on how transfers are carried out during planned and emergency transfers.

Under emergency conditions, $V_{motor,}$ $Freq_{motor,}$ and Θ will vary with time. When a main breaker opens due to sensing unhealthy voltage or for a protective trip, motors backfeed stored inertial energy into the dying motor bus. Prior to the trip, the fault itself has the capability of contributing to the phase angle difference. As inertial energy is turned into electrical energy, the bus's frequency decays and the voltage decays with the open circuit voltage time constant of the largest induction motor's open circuit voltage if the frequency doesn't decrease appreciably. As the frequency decays, the motor bus voltages slips with respect to the new source voltages. The smaller motors on the motor bus will also slip more than the larger motors with more inertia. The type of load on the motors and how it changes with frequency will also affect how each motor frequency decays.

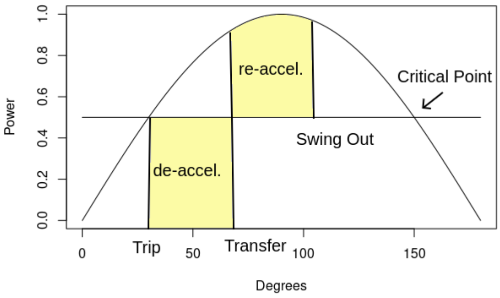


Fig 4. Equal Area Criteria for synchronous motors

Synchronous transfer of synchronous motors doesn't have a simple calculation to determine whether the transfer won't damage the motor. A synchronous motor will keep slipping as long as the electrical torque hasn't accelerated the motor to synchronous speed. The equal area criteria method is often used to determine if a motor will remain stable. In Fig. 4, the Equal Area Criteria plot shows the deceleration and re-acceleration regions. When a synchronous machines loses its source, it has no source of electrical power but it still has load (P_{load}). The phase angle of the motor will start lagging due to the only source of real power being inertial energy. When the bus is transferred to a healthy source, the motor starts to re-accelerate. It will swing out to the angle where the area cut out between the trip and transfer under P_{load} is equal to the area cut between the transfer and its max swing out angle provided it isn't greater than its critical point. The motor can be looked at as being synchronous when the inertial energy lost when it lost power is restored. If the motor angle swings past the critical point, it will start decelerate rather than re-accelerate and slips poles.

Additionally, it should be kept in mind that the half sine wave in the equal area criteria plot is linear with motor bus and new source voltage. If the motor bus voltage is suppressed before the transfer is initiated, the motor's phase angle will already be swinging out. When the transfer happens, the new bus's voltage may be suppressed some due to the current that is drawn to re-accelerate the transferred load. Both of these things can cause the motor's phase angle to swing out further than expected.

A. The behavior of common loads on loss of source voltage

Different loads have different characteristics in how they respond to a loss of source voltage. Loads interact and affect each other and the motor bus transfer.

A.1. Induction Motors

Upon the loss of a source, induction motors will start decreasing in frequency as stored inertial energy is converted into electrical power. Larger induction motors act like induction generators for smaller inertial loads. The motor bus voltage will decay with the largest open circuit motor time constant if the frequency hasn't decayed significantly. If an induction motor is dropped to help maintain the transfer, the phase angle of the bus will instantly shift in the slow direction. [8]

A.2 Synchronous Motors

Synchronous motors provide inertial support in maintaining the frequency liked induction motors but they provide more voltage support due to their external field excitation.

A.3 Adjustable Speed Drives (ASD)

Adjustable frequency drives have three distinctly different modes that they can operate in when their source is lost. It is key to note that these distinct modes are likely dictated by its loads and is not something that can be chosen due to it being beneficial to transferring load.

1. The ASD can remain connected to the bus and draws current from the other motors to maintain its load. This causes the bus frequency and voltage to decay more rapidly.
2. The ASD disconnects from the bus and coast until power is restored. Bus voltage and frequency are unaffected.
3. The ASD is forced into regenerative braking. If the ASD is utilizing a braking resistor the inertial energy is just wasted heating the resistor. If the ASD allows for reverse power flow, real power will flow back onto the motor bus and support the frequency. The ASD cannot provide reactive voltage support. [7]

A.4. Resistive Loads

Resistive loads cause the frequency and voltages to decay quicker and provide no frequency or reactive support.

IV. TYPES OF TRANSFERS

The types of transfers possible can be split down into two separate groups, closed and open. The open transitions are further subdivided into three subsets(fast, in-phase, and residual/fixed) each with two modes (sequential and simultaneous)

A. *Closed transfers*

Closed transfers involve closing in the tie to the new source and intentionally paralleling the two sources temporarily. The hazard with intentionally paralleling both sources is that it can increase the available fault current beyond the equipment ratings and the interrupting capability of the breakers. In addition, any angle differences between the sources will create power flows into and out of the facility. It can't be used for emergency transfers due to it exposing the healthy bus to a fault or unhealthy condition. The benefits of closed transfers are that it is simple and creates very little torque on the motors.

Closed transfers for planned situations might not be possible if there are standing phase differences between the two sources. This standing phase difference might be due to interconnecting at different points in the grid, present loads, or different transformer vector groups. If there is a sufficiently large phase difference, an open transfer is necessary for planned transfers.

B. *Open Transfers*

Open transfers consist of the transfer happening after the source breaker has opened. There are three basic types of transfers (fast, in-phase, and residual/fixed time) with two modes (sequential and simultaneous)

B.1 Modes of Transfer

There are two modes of transfer, sequential and simultaneous.

B1.1 Sequential Transfer

Sequential transfer supervises the closing of the tie breaker with verification that the breaker to the old source has opened. The breaker to the old source has to open before the tie breaker can start closing. If the old source breaker fails, the healthy source is not exposed to unhealthy voltages, the sources aren't momentarily paralleled, and no re-tripping is required.

This method is slower than simultaneous transfer but the difference between it and fast simultaneous transfer in terms of time, torques, and V/Hz decreases with faster breakers.

B.1.2 Simultaneous Transfer

Simultaneous transfers don't supervise of the closing the tie breaker with the opening of the unhealthy main breaker. This can result in the trip and close signal being sent at the same time. Paralleling of two sources is ,normally, avoided by the fact that breakers open faster than they close. The transfer time with simultaneous transfer is faster than sequential transfer due to not having to wait for verification that the old source breaker opened before closing the new source breaker.

Paralleling of both sources can happen if the old source breaker fails to open during transfer. The tie breaker will need to immediately re-trip to avoid a sustained paralleled condition and exposing the healthy new source bus to an unhealthy condition.

Simultaneous transfer is faster than sequential. The differences are less with faster breakers. Simultaneous transfer may be needed for systems where transfer speed is critical due to their being little available inertia or having synchronous motors. [9]

B.2 Types of Transfer

There are three basic types of open transfers (fast, in-phase, and residual/fixed) that can operate with either modes.

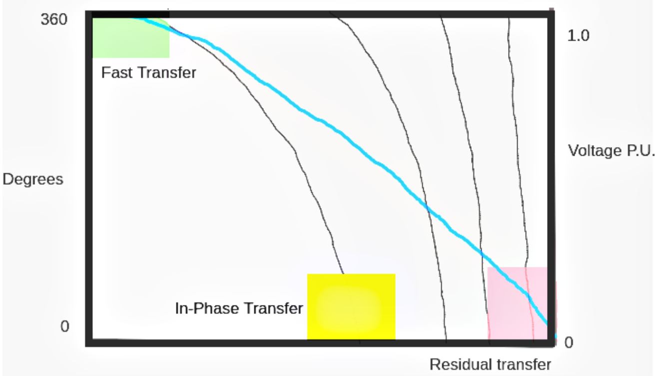


Fig . 5. A diagram showing the angle difference between the motor bus and the healthy bus as it slips and the decaying voltage (blue) on the motor bus. The color regions show where each type of transfer operate.

B.2.1 Fast Transfers

Fast transfers are defined as schemes that will close immediately provided the motor bus voltage is within the synchronization window. Fast transfers are supervised with a timer and if at anytime in the window the voltage magnitude, phase difference, and slip are acceptable the scheme will close the tie breaker. Fast bus transfers are ,generally, looked at as a one shot attempt before the motor bus start slipping excessively.

Fast bus transfers are the fastest of the open transition transfer types. This makes fast bus transfers attractive for systems that require fast transfers due to having low inertia or synchronous motors.

Fast bus transfer might not be possible on systems that have large standing angular differences or not enough inertia to prevent excessive slipping.

B.2.2 In-phase Transfer

In-phase transfers are similar to fast transfers in that there is a defined voltage, phase, and slip window but the scheme has to issue the close command attempt prior to the phasors synchronization due to the excessive mount of slip. The relay makes a calculation based on the phase, frequency, and slip frequency of the motor bus and closes the breaker ahead of the synchronization window taking into account the breaker closing time. It is necessary to have accurate breaker close time for the relay to accurately be able to calculate when to issue the close command to the tie breaker.

On systems that have large standing angular differences between the two sources, it may be necessary to use in-phase transfer for planned transfers to transfer load without interrupting the process.

The time it takes for the transfer to happen depends on the inertia of the system. In-phase transfer waits for the motor bus to slip until a synchronized transfer can be attempted. A motor bus with a large amount of inertia will take longer to slip into re-alignment than a motor bus with a low amount of inertia. A high inertia system might have a slip of 8.33 Hz/sec and transfer after 27 cycles. Allow inertia system with the same initial phase difference might have a slip of 31 Hz/sec and transfer after 13.3 cycles. [8]

B.2.1 Fixed and Residual Transfers

Fixed and residual transfers operate are similar in how they operate but they operate with different quantities. The 1.33 V/Hz limit for induction motors has three quantities in its calculation: voltage magnitude, frequency, and phase difference. In-phase and fixed transfers operate on residual voltage time voltage decay time to guarantee the transfer can happen without excessive torques.

Residual transfer assumes that once the voltage has dropped to around 20-25% on the motor bus, the V/Hz value will be below 1.33 V/Hz without any respect to the frequency or phase.

Fixed time transers are similar to residual transfer except that instead of measuring the voltage, it assumes after a certain period of time the voltage will have decayed such that the bus is below 1.33 V/Hz. On a bus with induction motors, the one with the largest open voltage motor time constant can be used to estimate the necessary fixed time. NEMA MG1 recommends waiting 1.5 open circuit time constants before transfer. [5]

With residual and fixed transfers, coordination must be done to verify that the motor contractors, fuses, and motor under voltage protection will not operate before the transfer. [5] Failure to do this could result in motors unintentionally being dropped before transfer. Some non-essential motors may need to be dropped due to the inability of the new source to re-accelerate all the motors at the same time and prevent motors from stalling Residual and fixed transfer are not considered fast enough to avoid interruptions to a process.

C. Determining facility's response

Most automatic transfer schemes are set based on past experiences or rules of thumb. This is often due to the expense of a study. The two methods that can be used to determine if a motor bus has enough inertia to successfully transfer are modeling the system or doing a live test.

If the system is modeled, all the motor, ASD, and auxiliary load information has to be collected from the manufacture and care must be taken when modeling the load and its frequency and voltage responses. Different loads provide different amount of inertial energy. Fan loads ,for example, provide more inertia than pump loads. Modeling the bus response can be difficult but it can be done in program like EMTP. [7]

In the model, the most impacting fault would be applied and the result would be inspected to determine if the chosen types of transfers would be successful or if mitigations would be needed, which could include something like dropping non-essential load to preserve the bus voltage and frequency before the transfer and then restarting it after transfer.

The second method is to do a live test and trip out the motor bus and watch how the voltage and frequency decays. This often is not an option to trip out the actual process while it is in operation is often not an option, but it is sufficient if representative load can be put on the motors and bus. The response allows for the voltage decay, frequency response, slip, V/Hz response to be observed. [7]

V. FINITE STATE MACHINES

Finite state machines are a tool that can be used to organize and layout your process while also making the logic easier to read and troubleshoot. State machines lend themselves to problems where there are clear and definable states and a set of rules can be developed as to how the state machine moves from state to state. Main tie main and other schemes lend themselves to state machines due to there being clear states and clearly defined conditions on when the system moves from state to state. State machines don’t change the logic needed for a process but provides a framework as to how to organize and execute the logic.

There are two types of finite state machines: Moore and Mealy. Either one can be implemented but this paper will focus on using Moore type state machines. Moore type state machines use the inputs and the state itself is the output.

Using state machines to develop controls logic has been common among controls engineers. The framework makes it easier to develop, read, and troubleshoot the logic. Additionally, the standard IEC-61131-3 includes Sequential Function Charts (SFC) as a standard means of programming PLCs. SFC is a graphical means of organizing the flow of logic with states, transitions, and outputs. An engineer or non-engineer can readily understand the flow of the logic. State machines can be created in PLCs without SFC, using ladder logic or structured text. Due to protective relays, scanning their logic similarly to PLCs, this logic in Boolean form can be used to create state machines.

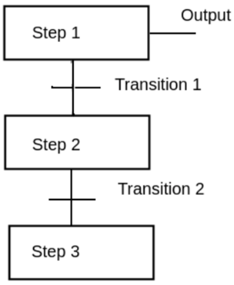


Fig. 5. IEC 61131-3 Sequential Function Chart.

A. Light Switch Example

Below is a Moore state diagram of a simple light switch state machine. This example will provide the framework as to how state machines can be created and used inside of relays.

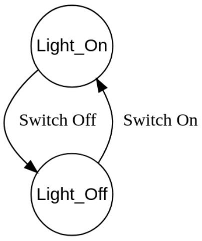


Fig. 6. Light switch Moore state machine

The outputs are the states, which is the light being on or off. The input and device that is causing the transition between state is the switch.

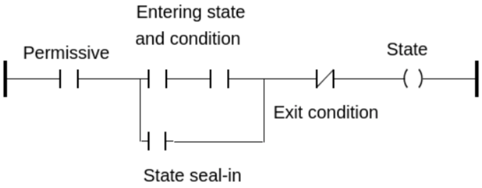


Fig. 7. General diagram of how to create a state in ladder logic. [4]

Fig 7 is a general diagram showing how to create a state machine with ladder logic in a PLC. PLC process their logic left to right and top to bottom in a sequential fashion. Protective relays often process their logic top to bottom in a similar fashion so the structure will carry over.

In the general diagram, there are five components. The permissive is something that initiates the process like a start button or blocks the process like a lockout. The entry conditions are the conditions and the states that can transition into the state. The seal in contact holds in the state until an exit condition is met. The exit conditions are the condition that allow the state to exit and tratnsition to another state. Multiple exit conditions are put in series. The exit condition for one state will be the same as the entry condition for another. The state bit can be used to execute the logic that is specific to its state.

The attachment Appendix 1. shows what the light switch state machine would look like with ladder logic.

The first two lines are used to pass the previous scanned bits into **Light_On** and **Light_Off**. The reason that this is done is that is that it prevents the device from activating more than one state in a scan. The logic is scanned left to right and top to bottom. The bits change as each line is scanned. If the **Light_On** was in place of the **Next_Light_On** coil on the 4th rung, when the switch was flipped from on to off, the **Light_Off** state's coil wouldn't energize due to **Light_On** ,now de-energized, blocking **Light_Off** from activating and latching in. Using the bits from the previous scan, in the present scan's logic prevents the state machine from making state changes based on partial results of the logic processing. Care must be taken to ensure that the order in which a device scans the logic does not affect the operation of the state machine.

The third rung defines the initial state. Logic must be included to identify what state it should be in on energization or when the permissive is activated. In the example, when the permissive is activated if none of the states are activated, the light is forced into the on state.

The fourth and fifth rungs define how the **Light_On** and **Light_Off** states are entered into and excited. The **Light_On** and **Light_Off** bits could be used in other logic to trip and close breakers and be included other ancillary logic that defines how transitions are made from state to state.

The result in this example is that two states have been created with defined transitions from one state to the other, an initial condition, and a permissive. This was created with five rungs of logic. It could have been made with less but it wouldn't have the framework that makes it more readable, and simpler to modify and troubleshoot. The states provide a clear indication how the device is progressing through the logic. Each transition is a simple set of readable logic that is segregated from all the other logic. When state machines aren't used, the combinational logic becomes less readable as it grows in size and more difficult to code, troubleshoot, and modify since it is not made up of small definable and segregated steps. States provide a means of creating an abstraction that allows the problem to be broken down into smaller digestible pieces.

B. Main-Tie-State Machine Example

The attachment Appendix 2. shows an example layout for a main-tie-main scheme. The states are defined and the transition describe how the logic advances from one state to another. The scheme has two branches that handle two possible conditions, the losing one or both sources at the same time.

The general operation for the scenario when one source is lost is that the unhealthy main opens and transfers the load to the healthy source. It stays in this state unless the unhealthy main becomes healthy again or the one healthy main loses its voltage. If the unhealthy main sees it's voltage restored, the scheme will attempt a closed transfer and close the main and then try to re-transfer its load by opening the tie breaker. If this is possible, it will have returned back to its initial state. If it loses its one healthy source while it was serving all the load with it, it will try to open the tie and main breaker and then enters a live source seeking state.

The general operation for the scenario when both sources are lost at the same time is that it opens both main breakers and then waits for one or both sources to return. If one source returns, it tries to close the main to that source and then tries to transfer load to the healthy source. It then waits for the other source to return to a healthy state to close its main and re-transfers the load back to its original state. If instead, initially, both sources are lost at the same time and return at the same time, it attempts to reclose both mains and bring the system back to its original state.

For simplicity of the diagram, it is assumed that there would be logic included to provide an identical for each source. Multiple lockouts were used to prevent the diagram connections from crossing each other in the layout. The logic path is strictly for automatic operations and doesn't include logic needing for a manual/automatic switch or reset after being locked out.

The purpose of going through this example is that it demonstrates how the abstraction simplifies the process of creating the logic for a main tie main scheme. It improves the general readability of the scheme such that a state diagram could be used to explain the scheme to non-engineers. Additionally, because each transition between states is clearly defined, it is very straight forward as to how to create the logic. Also, since the logic is clearly segregated between states and transitions, it is easy to add, remove, or modify states and transitions without worry that it will affect the other logic. More lines of logic might be necessary when using finite state machines, however, it become exponentially more difficult to create a scheme using unstructured combinational logic as the scheme gets more and more complex. It is essential ,however, for the state machine to account for all possible states.

VI. Conclusion

Main tie main schemes can be used to reduce interruptions in a facility by utilizing a redundant connection to the grid and incorporating an automatic transfer scheme. The automatic transfer scheme can utilize fast, in-phase, or residual/fixed transfers to shift load from one source to the other to maintain the process. The logic that determines how the transfer scheme operates can be simplified and made more straight forward and readable through the use of finite state machines by breaking down the scheme into small segregated steps.

VII. References

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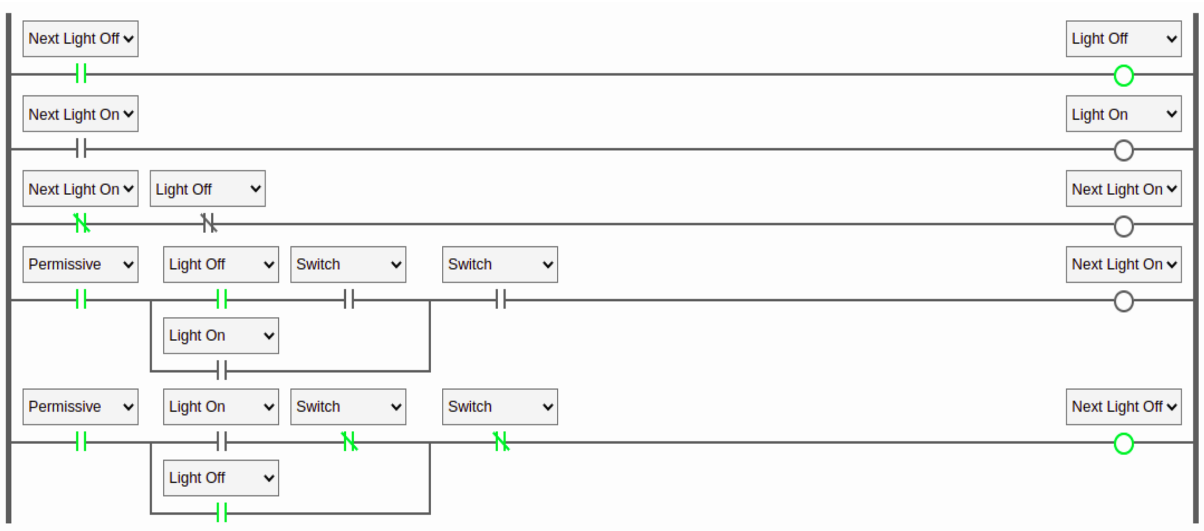
Appendix 1. Light switch state machine



Appendix 2. Main-Tie-Main Example