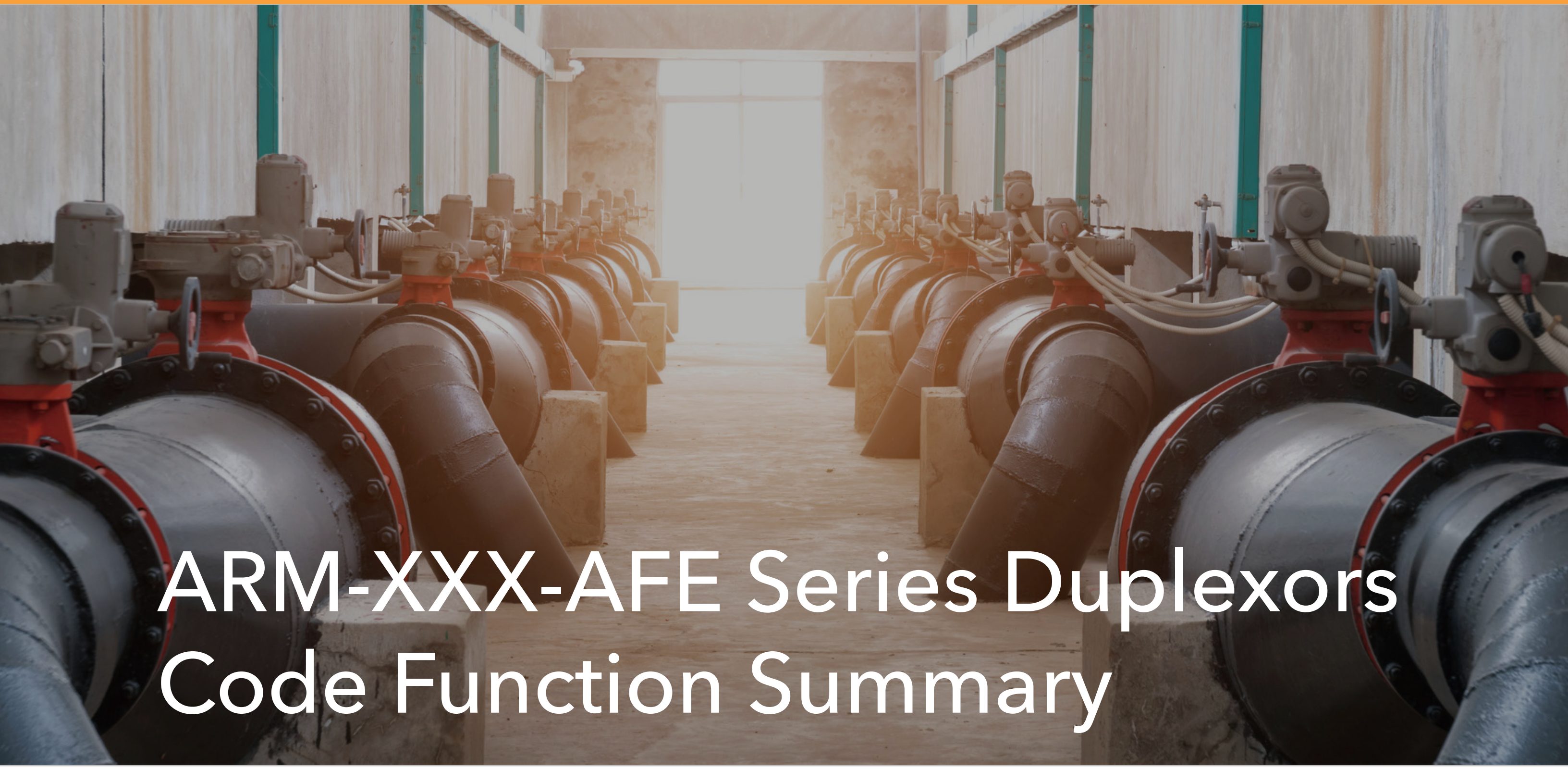

ARM-XXX-AFE Series Duplexors Code Function Summary

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The purpose of this technical whitepaper is to provide a comprehensive overview of the basic alternation operation of ARM Duplexors. This document explains the functions and features of ARM Duplexors, including their interface with float switches, automatic duplex alternation, configuration switches, alarm outputs, and LED indicators. It also discusses the highly beneficial fault detection algorithm used in these systems. Additionally, recommendations and considerations for system installation and operation are provided.

BASIC ALTERNATION OPERATION - NO FAILED SWITCHES

The ARM duplexors are integrated pump controllers providing the following functions in one unit:

1. Intrinsically Safe interface to connect with float switches in Hazardous Locations.
2. Automatic duplex alternation to extend load lifetime and efficiency by determining when to run each load and when both loads are needed to control level.
3. Configuration switches for selecting manual overrides for direct control or automatic operation.
4. Alarm output contacts provide feedback to alert maintenance when the system is operating outside acceptable limits.
5. LED indicators to show operators system status at a glance.

TERMINALS

Terminals #'s 1-6 which are wired to the float switch contacts to sense the level of the system. Terminal #1 is the common (DC ground of the controller), with the terminal #'s 2-6 being connected to the common by the float switches when the level is higher than the float. Terminal #'s 2-6 will be internally pulled to +5Vdc with reference to terminal #1 when they are open, and will be less than 2.0 Vdc when closed.

Terminal #7 is the "Hot" wire or the AC supply, and #8 is the Neutral or AC return. #9 & #10 are the relay outputs to drive the loads being alternated, and are internally connected to the hot wire to turn the pumps on. #11 & #12 are dry contacts for the alarm relay.

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The Alarm Relay will energize when an alarm condition, such as high level or control switch failure, is present. The Alarm Relay will remain energized until the alarm condition is resolved. For switch failure, switches determined to have failed must change state so that that all switches are in "legal" states (closed switches below open switches). For alarm level, the level must fall so that the second highest valid switch is open. This provides positive hysteresis for the alarm level.

In 2018, an indicator LED will be added for the alarm relay. When lit, this LED indicates that the alarm relay is energized, even when the alarm condition has been resolved. In that case, the TEST/CLEAR button may be pressed to clear the alarm condition, causing the alarm relay to de-energize.

The ARM-2011 will not energize the alarm relay for failed input status, but the switch failure LED will indicate failed input status.

CONFIGURATION SWITCH FUNCTION

There may be several switches on the housing of the unit, depending on the model number.

LOAD 1 HOA & LOAD 2 HOA (OMITTED FOR ARM-2003 & ARM-2010) – These switches may be used to directly control each load or to select automatic alternation. When set to OFF, the load will not energize. When set to HAND, the load will energize. When set to AUTO, the load will follow normal alternation.

Note that the second load output may be delayed for the inrush delay of up to 5 seconds if the other load has recently energized.

When an HOA switch is changed from OFF to AUTO, the corresponding load may immediately energize, if the current input calls for that load to be on.

LEAD SELECT (ALL MODELS) – This switch may be used to set lock the automatic load energization sequence. This does cause a load to be omitted (use HOA switches to omit a load).

When set to LOAD 1, load 1 is the lead load and load 2 is the lag load. When set to LOAD 2, load 2 is the lead load and load 1 is the lag load. When set to AUTO, normal automatic alternation is used.

Note that the HOA switches may still be used to force loads on or off, and will affect the automatic alternation sequence. If the LEAD SELECT switch is used to select a load as the lead load and that load's HOA switch is set to OFF, then neither load will energize when the Lead switch closes (because the other load is set as lag load). The lag load will energize when the Lag switch closes, provided its HOA switch is not set to OFF.

To ensure that neither load energizes, either set both HOA SWITCHES to OFF, or de-energize the system.

TEST/CLEAR (ALL MODELS) – This switch is a momentary push-button, and may be used to clear switch failures and increment the lead load. If no load is energized, the next lead load will energize while the button is pressed. If a single load is energized, the unit will alternate, de-energizing the current load and energizing the other. If both loads are energized, the lead load will be incremented, affecting the next load cycle.

AUTOMATIC ALTERNATION

<u>Four-switch Systems</u>

These systems have 4 float switches (closing from lowest to highest): Off, Lead, Lag, and Alarm. As level rises, the controller will turn on one load when the Lead switch closes, the 2nd load when the Lag switch closes, and close the alarm output when the alarm switch closes.

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As level falls, the alarm output will open once the Lag switch opens. Both loads will de-energize once the Off switch opens.

Note that since the Aux. Off switch input is not used, it is connected in parallel with the Off switch input. The Aux. Off switch is always read, and if left unconnected, it will be read as an open switch below a closed Off switch, interpreted as a result of a failing float switch. This may lead to improper operation.

<u>Five-switch Systems</u>

These systems have 5 float switches (closing from lowest to highest): Auxiliary Off, Off, Lead, Lag, and Alarm. With no failed switches, operation is identical to a 4-switch system.

The Auxiliary Off switch is used to protect against error conditions where higher float switches have failed closed. For example, if all other switches has opened, but the Off float switch fails closed, when the Aux. Off float switch opens, the ARM controller determines that the Off switch has failed, and will de-energize the loads. If there are more than one closed switch above the open Aux. Off switch, the FDA (Failure Detection Algorithm will determine the proper action).

Internal Switch Filtering

The firmware sets up a "tick" to facilitate the power-up and in-rush delays. This tick is also used to filter the float switch inputs. Each terminal is read once per tick. After 40 ticks, switches that are read as closed for more 24 ticks are read as closed and switches that are read as closed for fewer than 16 ticks are read as open. Switches that are read as closed for 17-23 ticks are kept at their previously state.

COMMON LEVEL CONTROL SYSTEM FAILURE MODES

Failed float switches prevent proper level sensing. In worst-case scenarios, this leads either to running unsubmerged (dry) pumps or overflowing.

For 2014 and later models, the worst-case error is defined as one that leads to pumping dry.

The reason for this is that even one failed pump can lead to overflow if a single pump cannot keep up with demand. If all pumps burn out pumping dry, an overflow is guaranteed if no intervention is made. Preventing pumping dry is key to preventing overflow. However, an overflow should never lead to pumping dry.

Recommendations

In a four-switch system, if the Off float fails closed, there is no lower float which can determine that the Off switch has failed. If it is not possible to install an Aux. Off switch, it is advisable to install another form of protection for the loads.
For example, current monitors may detect the decreased load or RTD's may detect over-temperature.

The Alarm Float switch is key to preventing overflow. There is no higher switch to determine that it has failed open. However, adding a second alarm switch would add redundancy. This extra switch could be added in parallel or connected to another circuit (use an ISO series isolated switch to provide another intrinsically safe connection).

Short Cycling

Care should be taken to avoid short cycling, when the loads cycle on and off rapidly. This can occur when either the float switches are placed too closely and/or when failed input switches shorten the load cycle.

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For example, consider a 5-Switch System: The 2nd switch is normally assigned as the Off switch, but if it fails in the open state, the 3rd (now 2nd passing) switch is assigned as the Off switch, and the 4th switch (now 3rd passing switch) is assigned as both Lead and Lag switch. When the 4th switch is closed, both loads come on (first one, then the other after the in-rush delay of 5 seconds) and the level should then fall until the new 3rd switch opens. If the 3rd and 4th switch were placed too closely together, then the loads could be turned on and off and back on in a short period of time.

FAULT DETECTION ALGORITHM (FDA)

The ARM Duplexors continually monitor inputs, and when float switches are opened or closed out of sequence, determine which floats to mark as failing. In the course of operation, floats may begin to function normally again - in this case the switches are cleared for duty and will again be used for pump control.

FAULT DETECTION AT POWER-UP

In early 2014, DEI improved fault detection at power-up. It was determined that, at power-up, if the lowest one or two switches were open and the rest of the switches closed, the ARM controller would not energize the loads. Since the loads were not energized, the maximum safe level was exceeded, causing damage.

This was undesirable because the quantity of closed switches was greater than the quantity of open switches, which should indicate that the open switches are likely failing and the closed switches were more likely to be working correctly.

The old code already set failing switches when an open switch was detected below a closed switch. All switches from the lowest open switch up to and including the highest open switch were set as failing. However, no attempt was made to apply a majority rule to guess which were correct and which were actually failing.

The solution was simple: add a section of code to count open and closed switches from the lowest open to the highest closed. Then apply a simple majority over the failing switches and set failing and passing switches accordingly.

After reviewing the possible worst-case scenarios for certain state(s), specific exceptions to this majority rule were added.

Note that when the Auxiliary Off Switch and the Off Switch are in the same state when power is applied, a 4-Switch system is assumed and the controller must only use the highest 4 switch inputs.

Once the Aux. Off Switch and the Off Switch differ in state, the controller changes to assume a 5-Switch system until power is reset. This can cause subsequent nuisance failures in 4-Switch systems if an attempt is made to rewire inputs while power is applied. DEI does not suggest changing wiring while power is applied, and a controller should be reset by removing power for several seconds after any wiring change.

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Control Switch (numbered for convenience)					
Case #	Aux. Off (1)	Off (2)	Lead (3)	Lag (4)	Alarm (5)
1	closed	closed	open	closed	open
2	open	closed	closed	closed	closed
3	open	open	closed	closed	closed
4	closed	closed	open	closed	closed
5	open	open	open	closed	closed
6	open	open	closed	closed	open

Table 1. Examples of power-up states with failing switches.

For case 1, Switch 3 is the lowest open switch and Switch 4 is the highest closed switch. Both these switches are considered failed since there is no majority. Without visually checking the floats, is impossible to know which float has actually failed. Both are ignored until a valid switch change validates them.

For cases 2 & 3, all switches are initially considered failed, as was done in the past. Now, since one or two open switches at the bottom are in the minority of the failing switches, only the open switches are considered failing and the closed switches are cleared and considered valid.

For case 4, switches 3, 4, and 5 are initially considered failed. There are more closed failed than open failed switches, so the closed switches (4 & 5) are cleared. Only switch 4 is ignored until a valid switch change validates it.

Cases 5 and 6 are special because switch 1 is ignored until it differs from switch 2. In both cases all switches are marked as failing and no pumps are energized until enough valid switch changes occur.

For case 5, if both bottom switches close in ascending order, those changes are legal, clearing those switches and both pumps energize. (Bottom switches are 1 & 2 if they change state at different times, or switches 2 & 3 if the jumper is installed.)

For case 6, if switch 5 closes, it validates switch 4 (and reassigned as Off Switch) and both pumps are energized. For the pumps to turn off, switch 5 must open, and then switch 4 must open.

FAULT DETECTION ALGORITHM WHEN RUNNING (AFTER POWER-UP)

***NOTE: FDA IS ACTIVE FOR ARM2011, but NOT used for the Alarm output. For that series, the "Control Switch Failure" LED is changed to "High Level Alarm" and the Alarm output is only energized based on float switch levels (closed after highest passing switch closes, opened after 2nd highest passing switch opens).

A flow chart for the fault detection algorithm is shown in figure one. The paragraphs of this section explain the operation of the key flow chart boxes.

A single change was made in 2014. Two sections of code for 75%/80% majority rules had been commented out. These sections were reactivated to help ensure a low likelihood of an unrecoverable lock-up.

Compare Current Input With Previous Input

The first step of the algorithm compares the previous positions of the control switches with the current positions of the control switches. This operation will be performed 100 to 1000 times a second. If the control switches have not changed in this period of time the rest of the algorithm is bypassed.

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Did More Than One Control Switch Change?

It is assumed that the level of a fluid in a reservoir or the pressure in a compressor system will not change significantly in less that 1 one-hundredth of a second. Therefore, no more than one control switch should change at a time. If two or more control switches change simultaneously there must be a wiring fault between the control switches and the duplexor. The switches that changed at the same time will be marked as failing and ignored for future computations.

Did a Failed Control Switch Change?

If a control switch that was previously thought to be failing changes position it is assumed that the switch is no longer failing or that it was never really broken to begin with. The switch is marked as passing and processing continues.

Is the Change "Legal"?

This is the first box to detect any control switch failure. Under normal conditions with a five control switch system there are only six "legal" control switch combinations. (See table 3.) If the switches do not match one of these combinations, then a failure is flagged.

Control Switch (numbered for convenience)				
Aux. Off (1)	Off (2)	Lead (3)	Lag (4)	Alarm (5)
open	open	open	open	open
closed	open	open	open	open
closed	closed	open	open	open
closed	closed	closed	open	open
closed	closed	closed	closed	open
closed	closed	closed	closed	closed

Table 2. "Legal" control switch combinations

Mark Switches Involved in Change as Failing

If an illegal change is detected this block determines which switches may be failing. An example of an illegal switch change is shown in table 4. On the line labelled "previous" is a legal switch combination. On the next line control switch 3 has opened out of turn. At this point it is impossible to determine whether control switch 3 is stuck open or control switch 4 is stuck closed. So, both switches are marked as failing (Indicated by boldface type.) and ignored in future computations.

	Control Switch				
	1	2	3	4	5
Previous	closed	closed	closed	closed	open
Current	closed	closed	**open**	**closed**	open
Next	closed	open	open	**closed**	open

Table 3. "Illegal" control switch change.

Did the Change Vindicate a Switch That Was Previously Thought To Be Failing?

Under certain circumstances a legal switch change may vindicate control switches that were previously thought to be failing. This is illustrated by the line in table 3 labelled "Next."

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In this case control switch 4 is the culprit and control switch 3 was operating normally all along. When control switch 2 opens it vindicates switch number 3. Switch number 3 returns to passing status and the broken switch is identified by process of elimination.

***Note that switches are considered to only validly close in ascending order. If switches close in a top-down manner, each additional closed switch will be treated as failing until the lowest expected switch closes. The lowest switch is always legal to close, unless closing simultaneously with another switch. A legal change of the lowest switch will clear the higher closed switches as passing (until an open switch below a closed switch is reached) and allow the controller to begin energizing the loads.

Compute New Output

This block looks at the positions of the passing control switches and determines whether the lead and/or lag loads should be energized, based on the number of closed passing switches.

<u>Zero passing switches:</u>
No loads are energized; Alarm will be energized for standard models due to failing switches (ARM2011 will not energize Alarm).

<u>One passing switch:</u>
The single switch will act as the Off, Lead, Lag, and Alarm switch.

<u>Two passing switches:</u>
The 1st switch will act as the Off switch.
The 2nd switch will act as the Lead, Lag, and Alarm switch.

<u>Three passing switches:</u>
The 1st switch will act as the Off switch.
The 2nd switch will act as the Lead and Lag switch.
The 3rd switch will act as the Alarm switch.

<u>Four passing switches:</u> (4-Switch System, normal operation)
The 1st switch will act as the Off switch.
The 2nd switch will act as the Lead switch.
The 3rd switch will act as the Lag switch.
The 4th switch will act as the Alarm switch.

<u>Four passing switches:</u> (5-Switch System)
The 1st switch will act as the Aux. Off switch.
The 2nd switch will act as the Off switch.
The 3rd switch will act as the Lead and Lag switch.
The 4th switch will act as the Alarm switch.

<u>Five passing switches:</u> (5-Switch System, normal operation)
The 1st switch will act as the Aux. Off switch.
The 2nd switch will act as the Off switch.
The 3rd switch will act as the Lead switch.
The 4th switch will act as the Lag switch.
The 5th switch will act as the Alarm switch.

A flow chart for the FDA is included on the last page for convenience.

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FAULT DETECTION ALGORITHM PERFORMANCE ANALYSIS

Performance With Five Control Switches Installed

When one switch fails, either stuck open or stuck closed, the duplexor will detect the failure, energize the alarm relay, and continue to operate the pumps without a noticeable loss in performance.

If two switches fail there are three scenarios that will cause problems. If control switches one and two are stuck closed the duplexor will not detect the failure and it will never turn the pumps off. If control switches one and three get stuck closed the duplexor will detect the failure but it will not turn the pumps off. The third problematic scenario occurs if control switches two and four are stuck open. In this situation the failure would be detected but the lift station would overflow because the pumps will never turn on.

If three switches fail the duplexor will operate normally approximately half of the time. The other half of the time the pumps will run dry or the lift station will overflow.

Should a fourth or fifth control switch fail the operation of the duplexor is not dependable.

Performance With Four Control Switches Installed

If only four control switches are installed, they should be connected to the terminals for control switches two through five and a jumper should be placed between the terminals for switches one and two.

If one switch fails, either stuck open or stuck closed, the duplexor will detect the failure, energize the alarm relay, and continue to operate normally with one exception. If the Off Switch fails closed it cannot be detected, preventing the ARM from turning the pumps off. This is the reason for using the 5-Switch system, as using two Off switches can prevent this error.

If two switches fail the duplexor will operate normally approximately half of the time. The other half of the time the pumps will run dry or the lift station will overflow.

Should a third or fourth control switch fail the operation of the duplexor is not dependable.

Performance At Power-Up

With the inclusion of the "best-guess" case table now used at power-up, accuracy of function is improved in most cases. For example, in the case of a single switch failure causing three switches marked as failing in the past, we now have a 2/3 chance of guessing correctly instead of ignoring all the switches and making output decisions based on limited information.

In all cases, a wrong guess leading to a wrong decision in the new model would have led to a similar wrong decision in the old model.

Possibility of Irrecoverable Lock-up

It is possible that a higher switch could close first, and then other, lower switches closed afterward. The old code (Pre-2014) did not clear these switches as they closed until the lowest switch closed. If the bottom two closed simultaneously, both were counted as failures, meaning all switches were set as failed, preventing outputs from ever turning on. At this time, this requires enough failures that this is considered acceptable.

The FDA is not intended to eliminate failure completely, but rather to reduce the likelihood of irrecoverable failure.

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DEI warns of the possibility of failure, and that all customers should design controls to fail safely. This warning can be extended to include designing systems to account for component failure to avoid system-wide failure.

Adding External Circuitry to Avoid Worst-Case Scenarios

Pumping stations are often in remote locations, which require hours of travel prior to service. As explained above, the ARMXXXAFE series alternators are not foolproof since it is not possible to determine which float switches are failing 100% of the time. Systems should be designed to prevent possible errors in switch sensing from causing overflow or pumping dry.

These alternators are designed to allow overflow before allowing pumping dry. If either situation is completely unacceptable, adding external circuitry may add extra layers of protection against catastrophes (see recommendations on page 3).

A flow chart for the FDA is included below.