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Optimization of an Enhanced Backwash Filtration System for Produced Water Re-Injection in Oilfield Operations

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Abstract
Produced water management is an issue in oil and gas operations and it is more of a concern in mature parts of the fields where the amount of produced water is increasing and placing an additional burden on the treatment and reinjection systems. Filtration units used in the produced water reinjection (PWRI) are highly vulnerable to fouling, and conventional backwash methods that are based on a constant schedule or a constant threshold often led to poor performance, waste water and energy use, and erratic effluent quality. These are more so with the Niger Delta where the nature of the produced water is extremely unpredictable and there is a high level of operational constraint. This paper also simulates and validates through simulation a superior backwash filtration control algorithm that has been developed using Emerson DeltaV Distributed Control System. The suggested solution is a dual-vessel duty/standby filtration system with automated vessel changeover and backwash activation, based on real-time differential pressure measurements. The philosophy of the control allows non-simultaneous isolation or backwashing of the vessel, which is supported by the solid interlocks and the state-it-is-logic. The approach taken by the methodology is simulation-based, using detailed control narratives, Sequential Function Charts (SFCs), operator-friendly Human Machine Interface (HMI) graphics, and control configuration within DeltaV Explorer. Dynamic simulation was used to test system performance under different fouling conditions to ensure logic integrity, operating safety and responsiveness. Findings have shown that a backwash technique based on differential pressure enables more effective facility operation in terms of backwash efficiency and economy, real-time flow continuity, and operator situational awareness, thanks to easy-to-understand graphics and vivid state indicators. The research finds that algorithm-based backwash control is a viable, dependable, and scalable solution to sustainable produced water treatment and reinjection, which can be successfully applied to the oilfield processes in the Niger Delta and beyond.

Keywords: *Produced water reinjection, backwash filtration, differential pressure, DeltaV distributed control system, fouling control*

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I. INTRODUCTION

One of the largest streams of waste in oil and gas production is produced water, and the quantity of it grows considerably with the maturity of oilfields [2]. The management has become more demanding due to the fact that water produced contains suspended solids, dispersed oil, dissolved salts, and heavy metals and other contaminants whose composition depends on the conditions of the reservoirs and operations [2],[3]. Poor water management in places of operation like the Niger Delta, which are sensitive to the environment, may impact on the reliability of operation and the safety of the environment.

Filtration has a significant role in produced water reinjection systems since it can manage solids and remaining oil that can inhibit injectivity and cause formation damage [5]. Nevertheless, filtration units are very susceptible to fouling, pressure accumulation, and loss of permeability, whereas conventional backwash systems that rely on fixed timetables or fixed values frequently result in ineffective cleaning, a fluctuating performance and waste of water and energy [2].

This problem is more acute in the Niger Delta, whereby the nature of produced water is highly fluctuating and the restrictions of operations are high [8]. The current backwash filtration systems are not responsive to variations in the quality and rate of influent flow and contaminant loading, leading to either over-backwashing or under-cleaning [2]. The specific issue that the given research focuses on is the absence of an adaptive and performance-based backwash control strategy capable of minimizing the use of resources without compromising the efficiency of filtration and the standard of the produced water reinjection under the conditions of variable operation.

II. REVIEW OF RELATED WORKS

Recent research indicates that backwash performance has gained prominence regarding produced water reinjection since the filtration stability directly influences injectivity, water recovery and operating efficiency. [9] showed that the online adaptive backwash scheduling of a pilot membrane system enhanced productivity and stability compared to fixed cycles. Nonetheless, it did not scale to media filters, restricting its direct application to larger oilfield filtration systems.

[10] also demonstrated that the performance of the backwash is highly contingent on the trigger conditions, as opposed to only on fixed timing. Their ultrafiltration test of the engineering scale was able to recognize an optimal intermediate TMP trigger and demonstrate that backwash time and chemically enhanced frequency of backwash largely influence net water recovery. Nevertheless, the paper lacked region-specific deployment recommendations and field-ready control algorithm to implement in real-time.

[11] presented the field-scale data that the optimized spacing between the backwash can enhance the stability of the filtration process and ensure the quality of injection during the extended working time. Their pilot outcomes revealed that better backwash timing was beneficial in maintaining performance and minimizing injector stimulation. The real decision rationale of the optimization was not, however, revealed in a generalized form that operators could directly apply.

[12] affirmed that the success of reinjection is directly related to solids and oil control, whereas [5] indicated that, despite the efficacy of membrane systems to enhance the quality of effluents, energy constraints and inefficiencies of the backwash are still significant. Likewise, other related works on fouling behavior determined that the fouling process is nonlinear and strongly dependent on operating conditions, making fixed backwash schedules inherently inefficient.

The practical necessity of better control is also justified by studies that are aimed at the Niger Delta. [7],[13]., and Isehunwa and Onovae (2011) emphasized the low quality of produced water, the gaps in the regulations, and the lack of infrastructure in the area, but none of them suggested an engineering control approach to the adaptive backwash optimization.

Overall, the related literature shows continued advancements in the knowledge regarding fouling, reinjection sensitivity, and backwash optimization, but it also indicates the existing deficiency: the existing literature has not resulted into a practical, adaptive, and differential-pressure-based backwash control framework that can be applied to produced water reinjection systems operating under varying conditions in the Niger Delta.

III. METHODOLOGY

3.1 Simulation-Based System Design Approach

This study adopted a simulation-based design approach to develop and validate the enhanced backwash filtration control system. The control logic was implemented and tested in the Emerson DeltaV Distributed Control System to evaluate sequencing, safety, and operational behavior without field deployment.

A dual-vessel duty/standby configuration was simulated, with differential pressure used as the primary indicator for fouling detection and backwash initiation. Sequential Function Chart (SFC) logic and valve-feedback-based interlocks governed vessel changeover and backwash operations.

The simulation validated the logical integrity and feasibility of the proposed control strategy for produced water reinjection applications. The architecture of the developed system is shown in Figure 1**.**

3.2 Simulation tools

The project was developed, simulated, and evaluated using the Emerson DeltaV Distributed Control System (DCS) software suite, which provided an integrated environment for control algorithm design, system configuration, operator interface development, diagnostics, and performance analysis.

a. DeltaV Control Studio

DeltaV Control Studio was the primary engineering tool for designing and implementing the backwash filtration control algorithms. The software supports IEC 61131-3–compliant programming and enables the development of modular control strategies using Function Block Diagrams (FBDs) and Sequential Function Charts (SFCs).

In this project, Control Studio was used to:

i. Develop differential-pressure–based backwash logic and vessel changeover sequences
ii. Configure interlocks, mode selection (auto/manual), and safety logic
iii. Perform offline simulation and validation of control behavior prior to deployment

This approach reduced commissioning risk and ensured logical integrity under varying fouling scenarios.

b. DeltaV Explorer

DeltaV Explorer served as the system architecture and configuration platform. It was used to define the overall control system structure, including controllers, I/O assignments, device placeholders, and network topology.

Key functions in the project included:

i. Controller and module assignment
ii. FOUNDATION Fieldbus device integration
iii. System commissioning and configuration management

DeltaV Explorer ensured consistency between control logic, hardware mapping, and system deployment.

c. AMS Device Manager

AMS Device Manager was employed for instrument and asset management. The software provided advanced diagnostics, configuration, and health monitoring of intelligent field devices connected via FOUNDATION Fieldbus and HART.

Its role in the project included:

i. Monitoring device health and communication status
ii. Supporting predictive maintenance through diagnostic alerts
iii. Enabling remote configuration and parameter adjustment

This enhanced reliability and reduced troubleshooting effort during simulation and testing.

d. DeltaV Diagnostics

DeltaV Diagnostics was used for system-level health and fault monitoring. It provided real-time status of controllers, networks, and communication paths using visual indicators and event logging.

The tool supported rapid identification of configuration errors, communication failures, and abnormal system behavior, thereby improving system robustness during validation.

e. DeltaV Operate (iFIX Graphics)

DeltaV Operate, based on the iFIX graphics environment, was used to develop the Human–Machine Interface (HMI). Operator displays were designed to be intuitive and state-aware, supporting effective monitoring and decision-making.

Functions included:

i. Dynamic process graphics and valve/transmitter animations
ii. Alarm management and mode selection
iii. Operator faceplates for real-time interaction

The HMI improved situational awareness and minimized operational error during backwash and vessel changeover operations.

f. Process History View (PHV)

Process History View (PHV) was utilized for trend analysis and performance evaluation. Integrated with the DeltaV Continuous Historian, PHV enabled the visualization of real-time and historical data.

In this project, PHV supported:

i. Analysis of differential pressure trends and backwash frequency
ii. Validation of algorithm performance under simulated fouling conditions
iii. Post-event review for optimization and tuning

PHV provided the analytical foundation for assessing control effectiveness and system stability.

3.3 System Framework

Figure 1 illustrates the functional interactions among control modules in the process control system, highlighting the flow of signals across the measurement, decision-making, and actuation layers.

At the measurement level, transmitters provide real-time process variables (such as pressure, temperature, or flow) to the Transmitter Control Module. This module performs signal conditioning and validation before forwarding the processed data to the Sequential Function Chart (SFC) Module, which serves as the central coordination unit for executing control logic.

The SFC Module governs system behavior by executing predefined control sequences and interlocks. It interacts bidirectionally with the Valve Control Module, which translates logical decisions into actionable control signals. Additionally, the SFC module receives operational inputs from the Mode-Selection Module, allowing switching between control modes such as manual, automatic, or maintenance, thereby ensuring operational flexibility.

The Valve Control Module communicates with the Valve Coupler Module, which acts as an interface between control logic and physical actuation. The Valve Coupler Module distributes output commands to the valve solenoid to enable valve actuation and simultaneously receives valve feedback signals (e.g., position or status) to confirm execution and support closed-loop control.

Overall, the framework demonstrates a structured interaction whereby measurement signals are processed and evaluated by a Sequential Function Chart (SFC), which then issues commands through intermediate control modules to final control elements. Feedback from field devices ensures accurate and reliable process regulation. This modular approach enhances system reliability, maintainability, and scalability in industrial automation environments.

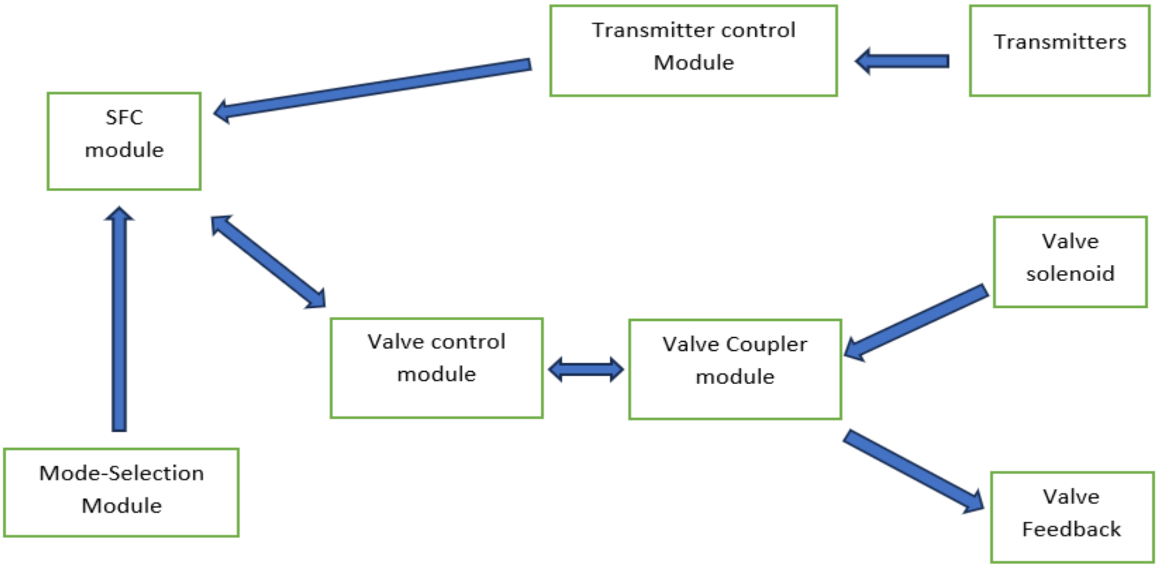


Figure 1: System Framework

3.4 Communication Structure

The process control system employs a hierarchical architecture comprising supervisory, control, interface, and field levels to ensure efficient monitoring and regulation, as shown in Figure 2.

At the supervisory level, the Engineering Workstation (Pro+ or EWS) facilitates system configuration, control logic development, and diagnostics. It enables engineers to design, modify and download control strategies to the system. Complementing this, Operator Workstations (Human–Machine Interface, HMI) provide real-time visualization of process variables, alarm management, and operational control, thereby supporting plant operators in decision-making and process supervision.

The control layer is anchored by the Process Controller (PK Controller), which serves as the core computational unit. It executes control algorithms, such as PID control and interlocks, processes incoming signals from field instruments, and generates appropriate output commands to maintain process stability and safety.

The interface layer consists of Input/Output (I/O) Cards and MEGA Blocks (Marshalling Panels). The I/O modules perform signal conditioning and conversion, translating analogue and digital signals between the controller and field devices. The MEGA block serves as a structured termination point, consolidating multiple field wiring into a single pair while ensuring maintainability and signal integrity.

Supporting the system is a Power Supply Unit that provides regulated, reliable electrical power (typically 9-24 VDC) to all control and interface components, often incorporating redundancy to enhance system availability.

At the field level, Field Devices—including sensors (e.g., pressure transmitters) and actuators (e.g., control valves)—serve as the physical interface to the process. These devices supply real-time measurements to the controller and execute control actions as commanded.

Overall, data flows from field devices through the interface layer to the controller for processing, while control commands propagate in the reverse direction to regulate the process. This structured architecture ensures robustness, scalability, and efficient process automation.

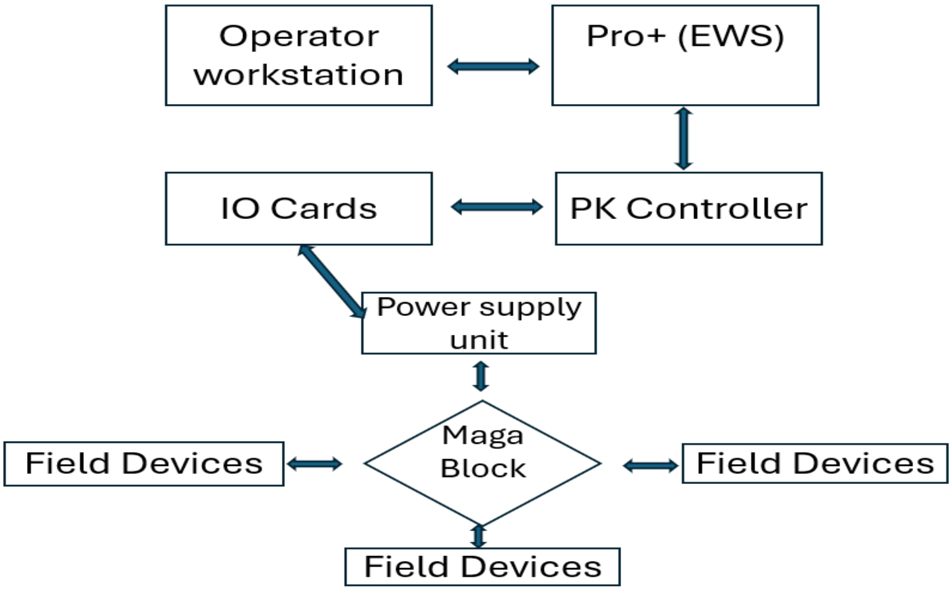


Figure 2: Communication structure

3.5 Control Philosophy and Implementation

The control strategy was based on real-time differential pressure monitoring across the active filter vessel. When the differential pressure reached the predefined high threshold, the standby vessel was automatically placed in service, after which the fouled vessel was isolated and subjected to backwash. Backwashing continued until the differential pressure dropped to the low setpoint, indicating recovery of filter permeability. This control philosophy ensured uninterrupted filtration, prevented simultaneous vessel isolation, and maintained a continuous process flow path. The main instrumentation and setpoints used for this logic are summarized in Table 1, while the sequence logic for vessel changeover is illustrated in Figures 3 and 4**.**

Table 1: Instrumentation and Setpoints

Tag	Description
DPT-A	Differential Pressure Transmitter – FV-A
DPT-B	Differential Pressure Transmitter – FV-B
DP_HH	High differential pressure setpoint (backwash trigger)
DP_LL	Low differential pressure setpoint (backwash completion confirmation)

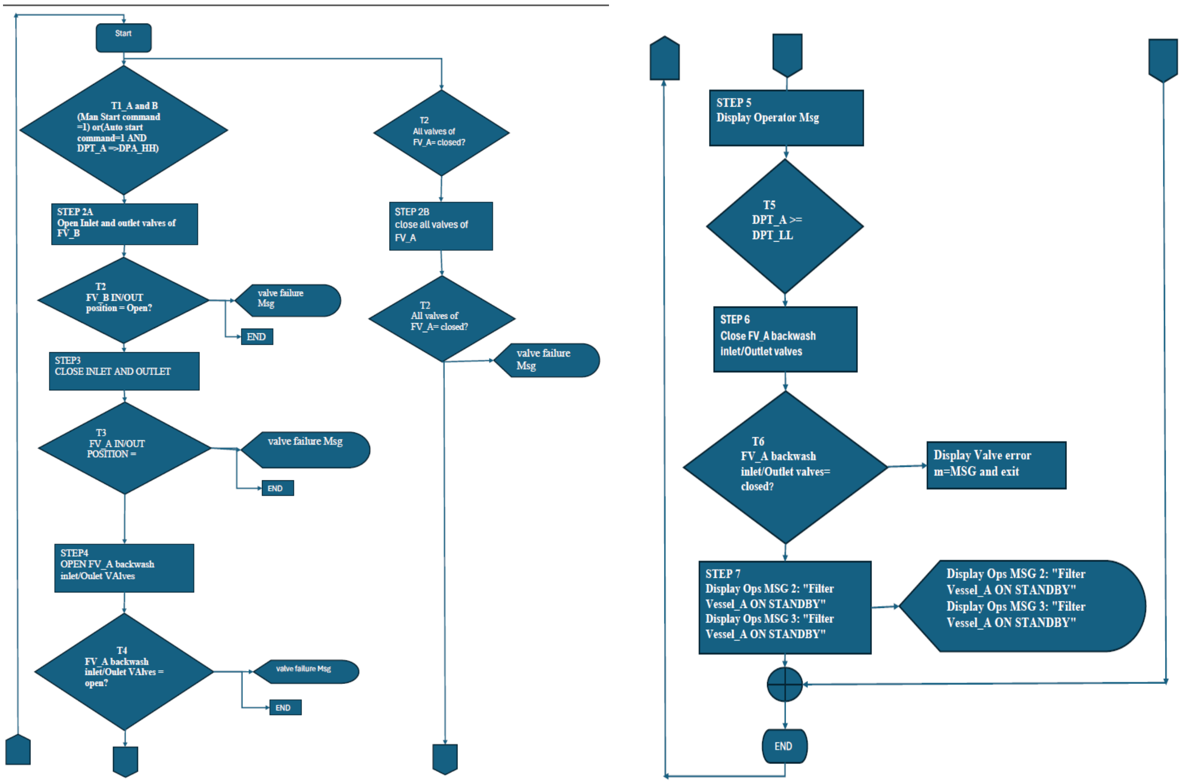
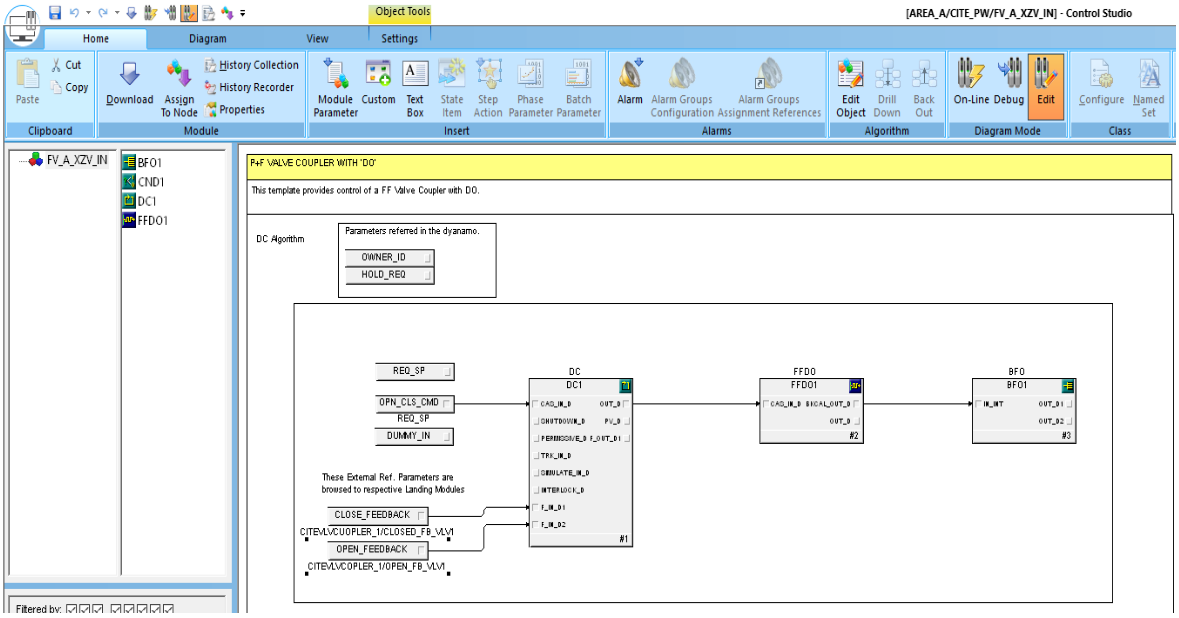


Figure 3 and 4 Sequence flow chart- FV-A to FV-B change over (Part 1)

The control algorithm was developed in DeltaV Control Studio using modular control blocks for valve actuation, valve feedback handling, differential pressure acquisition, sequential function control, and mode selection. Internal communication among these modules was structured to support deterministic command execution and feedback verification. The key implementation views are presented in Figure 1- System framework (module interaction), Figure 5 for the valve control module, Figure 6 for the valve coupler configuration, Figure 7 for the differential pressure control module, and Figure 8 for the vessel changeover and backwash Sequential Function Chart.



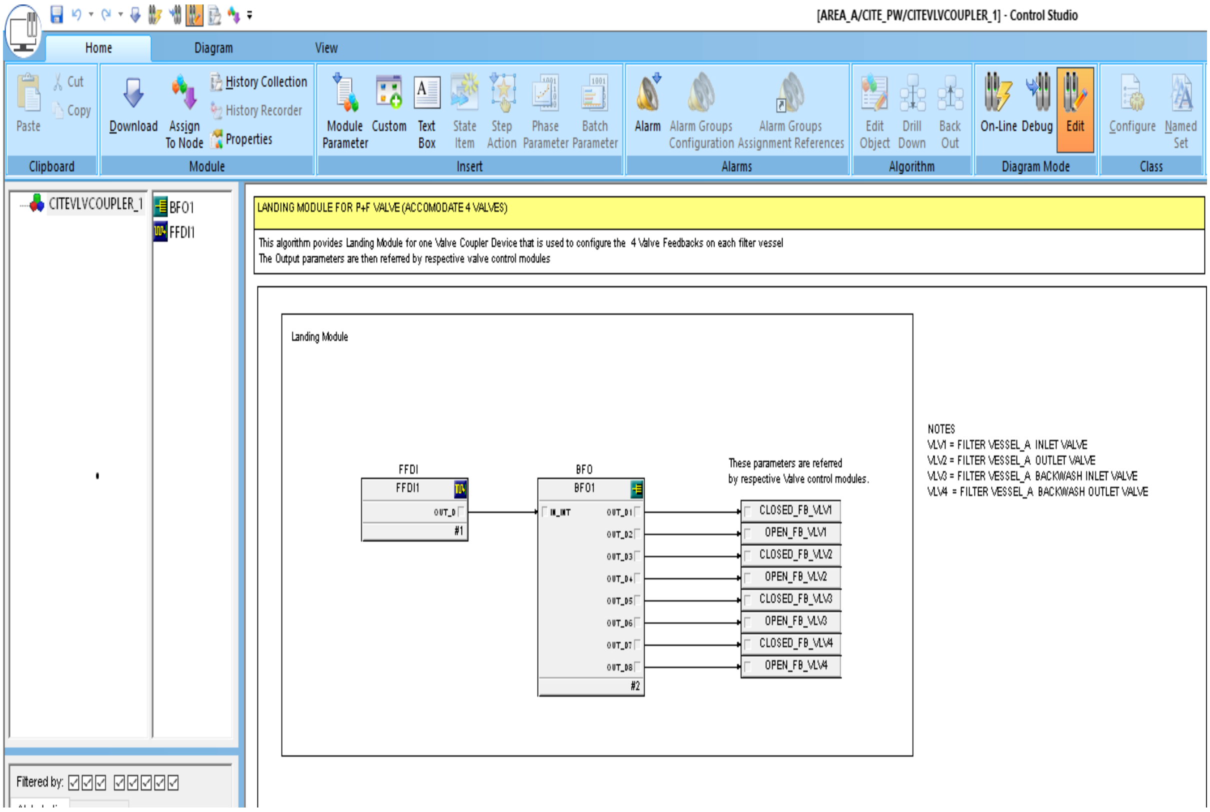
P+F VALVE COUPLER WITH 'DO'

This template provides control of a FF Valve Coupler with DO.

Parameters referred in the dyanamo.

These External Ref. Parameters are browsed to respective Landing Modules

Figure 5: Valve control module with feedback from valve coupler



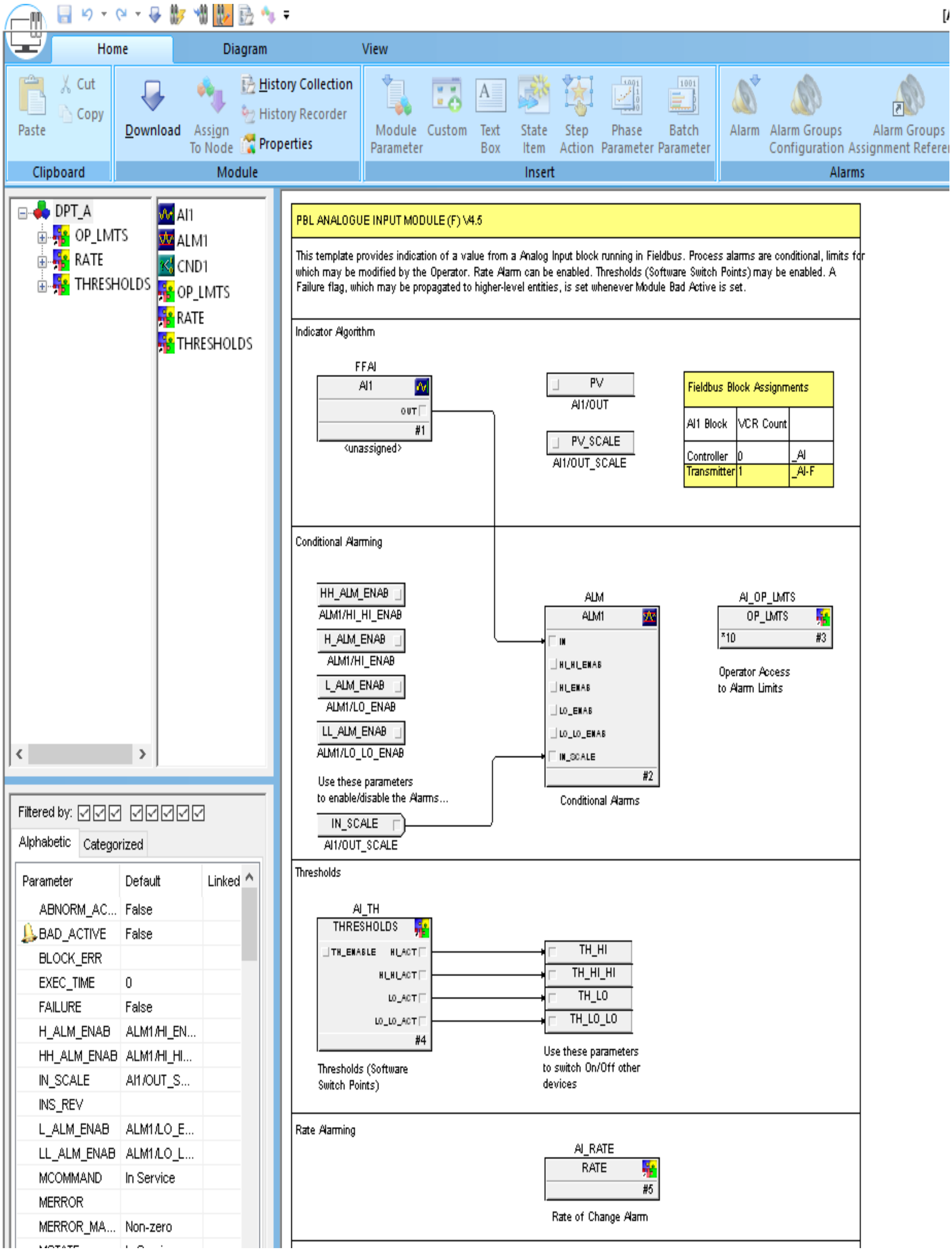
LANDING MODULE FOR P+F VALVE (ACCOMODATE 4 VALVES)

This algorithm povides Landing Module for one Valve Coupler Device that is used to configure the 4 Valve Feedbacks on each filter vessel
The Output parameters are then referred by respective valve control modules

These parameters are referred by respective Valve control modules.

NOTES
VLV1 = FILTER VESSEL_A INLET VALVE
VLV2 = FILTER VESSEL_A OUTLET VALVE
VLV3 = FILTER VESSEL_A BACKWASH INLET VALVE
VLV4 = FILTER VESSEL_A BACKWASH OUTLET VALVE

Figure 6: Valve coupler module for Filter vessel-A



PBL ANALOGUE INPUT MODULE (F) V4.5

This template provides indication of a value from a Analog Input block running in Fieldbus. Process alarms are conditional, limits for which may be modified by the Operator. Rate Alarm can be enabled. Thresholds (Software Switch Points) may be enabled. A Failure flag, which may be propagated to higher-level entities, is set whenever Module Bad Active is set.

Fieldbus Block Assignments

AI1 Block	VCR Count	
Controller	0	_AI
Transmitter	1	_AI-F

Parameter	Default	Linked
ABNORM_AC...	False	
BAD_ACTIVE	False	
BLOCK_ERR		
EXEC_TIME	0	
FAILURE	False	
H_ALM_ENAB	ALM1/HI_EN...	
HH_ALM_ENAB	ALM1/HI_HI...	
IN_SCALE	AI1/OUT_S...	
INS_REV		
L_ALM_ENAB	ALM1/LO_E...	
LL_ALM_ENAB	ALM1/LO_L...	
MCOMMAND	In Service	
MERROR		
MERROR_MA...	Non-zero	

Figure 7: Designed Differential Pressure configuration

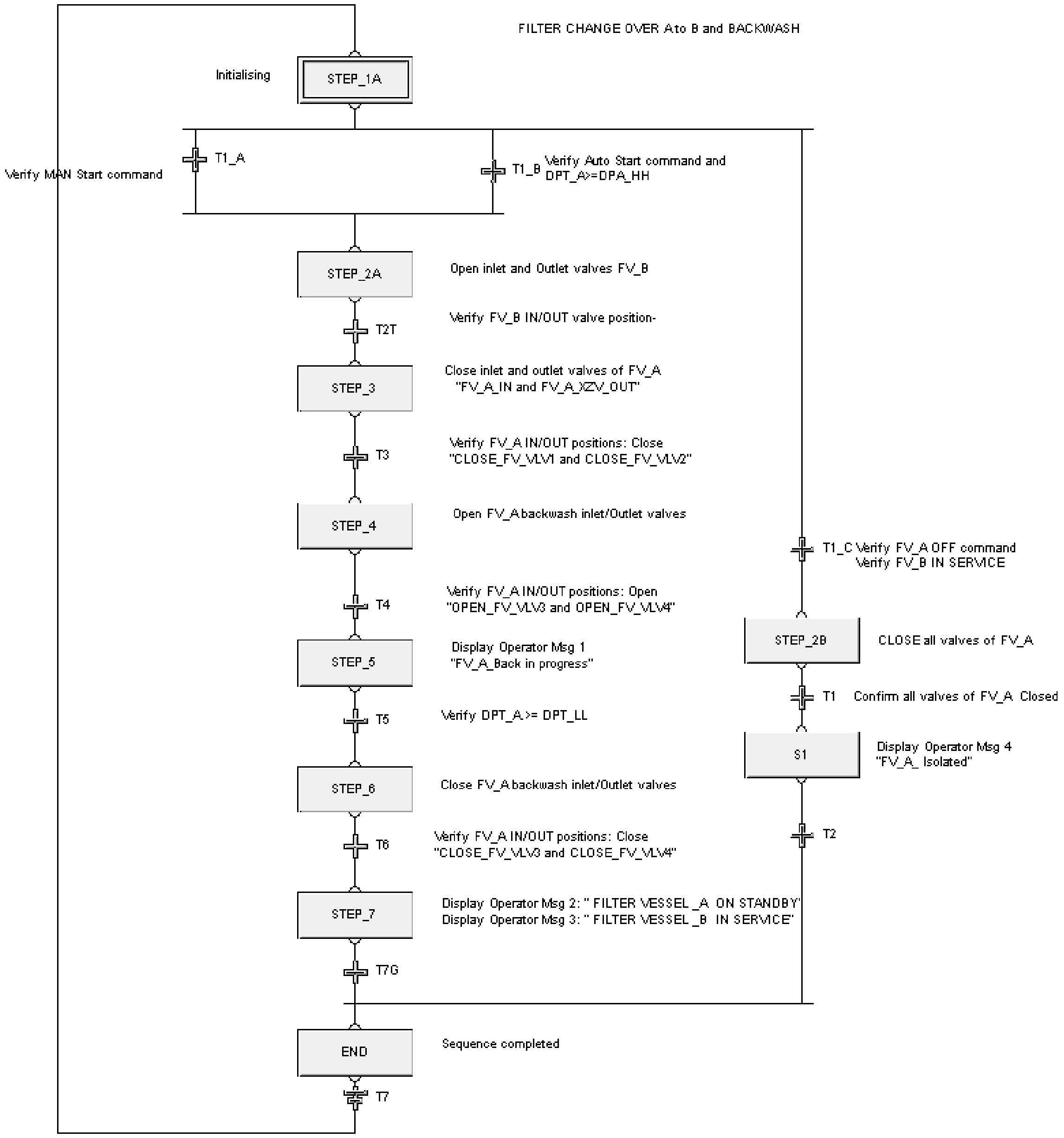
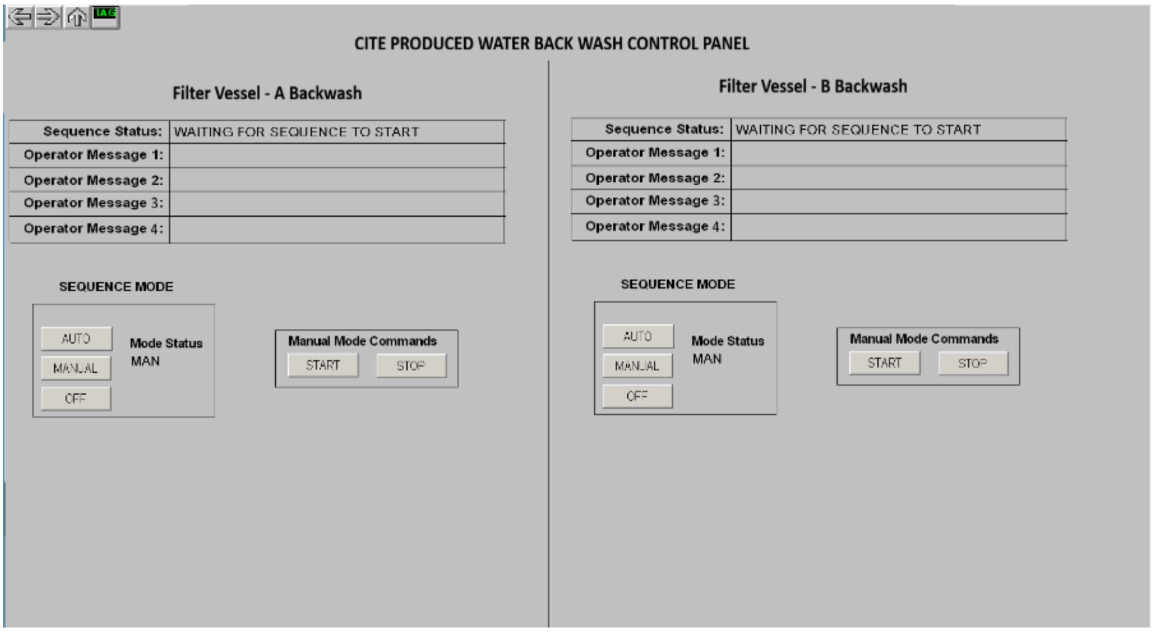


Figure 8: Sequential Function Chat for vessel change over

To support operator interaction and monitoring, a Human Machine Interface was developed using DeltaV graphics. The HMI provided real-time visualization of filter states, valve positions, alarms, and process transitions, thereby improving operator situational awareness and ease of supervision during filtration and backwash cycles. The principal interface views are shown in Figure 9 for the operator console, and Figure 10 for the valve coupler faceplate.



CITE PRODUCED WATER BACK WASH CONTROL PANEL

Filter Vessel - A Backwash

Sequence Status: WAITING FOR SEQUENCE TO START
Operator Message 1:
Operator Message 2:
Operator Message 3:
Operator Message 4:

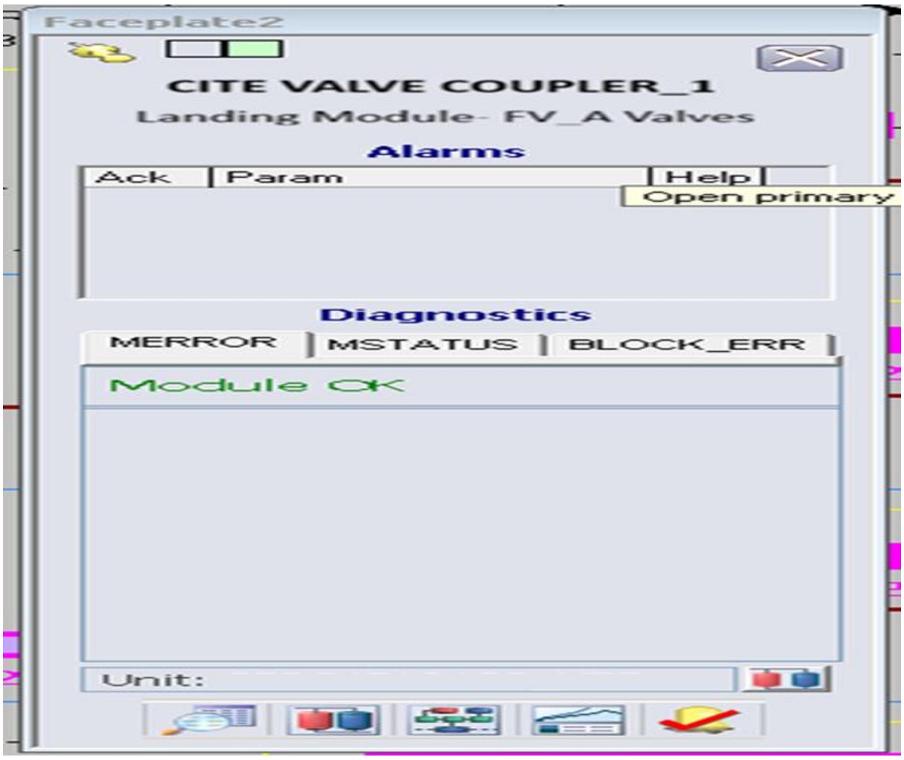
Mode Status: MAN

Filter Vessel - B Backwash

Sequence Status: WAITING FOR SEQUENCE TO START
Operator Message 1:
Operator Message 2:
Operator Message 3:
Operator Message 4:

Mode Status: MAN

Figure 9: Developed HMI for Operator Console



Faceplate2

CITE VALVE COUPLER_1

Landing Module- FV_A Valves

Alarms

Diagnostics

MERROR: Module OK

Unit:

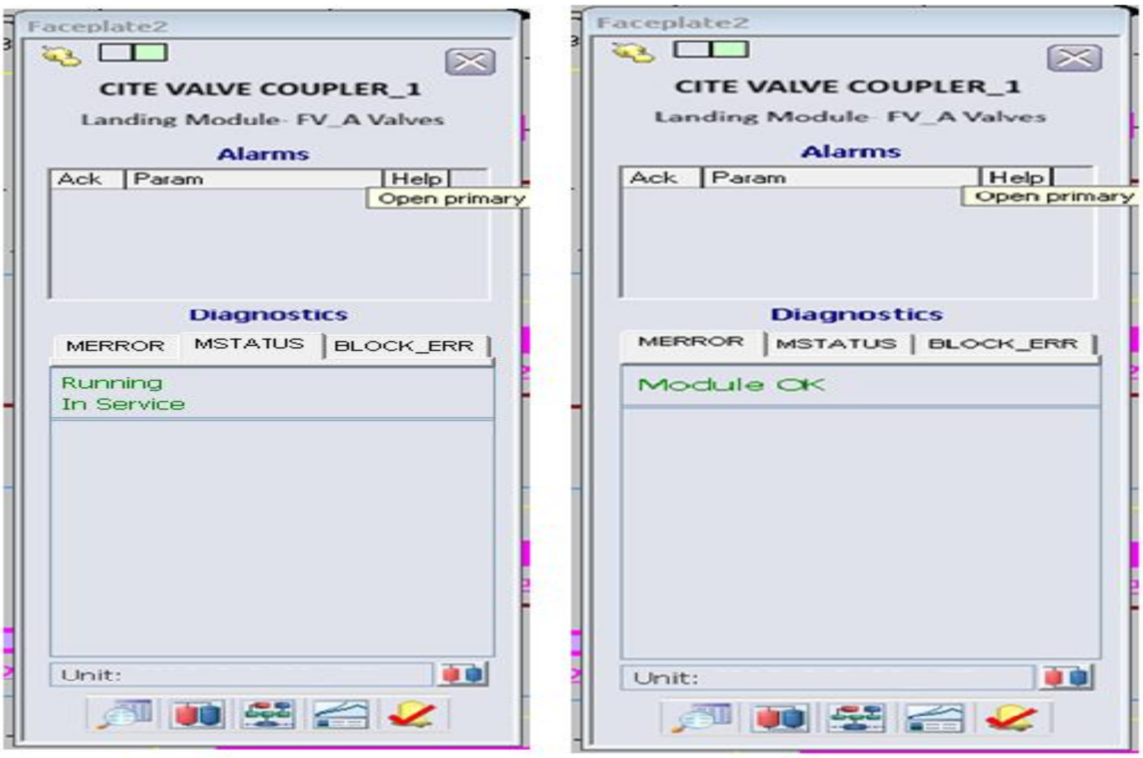
Figure 10: Designed valve coupler face plate

System evaluation was carried out through dynamic simulation under different fouling conditions. Data were obtained from simulation-based logging, event records, alarm behavior, valve response, and process trends within the DeltaV environment. Performance assessment focused on logic integrity, correct sequence execution, alarm and trigger response, operator interface functionality and continuity of flow during backwash operation. The main evaluation outputs reported in the study are summarized in Table 2, which presents simulation of filter fouling and vessel transitions, and Table 3, which presents the control system performance indicators.

IV. RESULTS AND DISCUSSION

4.1 Results

The developed differential-pressure-triggered backwash control system was successfully implemented and verified in the Emerson DeltaV simulation environment. The results showed that the control modules operated without configuration or execution faults, confirming that the designed algorithm was logically sound and stable for filtration monitoring and backwash control. This was verified through diagnostic indicators such as MERROR, MSTATUS, and BLOCK_ERR, all of which indicated normal operation during testing. The most relevant visual for this result is Figure 11: Module diagnostics on faceplate.

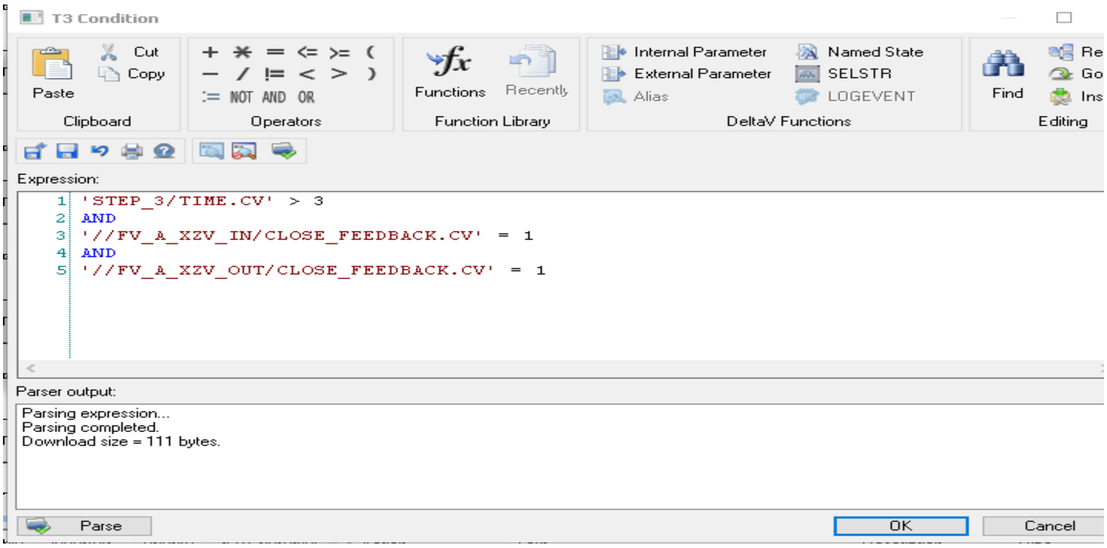


Running
In Service

Module OK

Figure 11: Module diagnostics on faceplate

The logical expressions used in the control strategy were also successfully validated using the DeltaV Parse Function. This confirmed that the programmed expressions for differential-pressure monitoring, valve actuation, and backwash initiation were syntactically correct and executable within the control environment. The most relevant figure supporting this stage of verification is Figure 12: Parse Test of T3 expression.



Expression:

```
'STEP_3/TIME.CV' > 3
AND
'//FV_A_XZV_IN/CLOSE_FEEDBACK.CV' = 1
AND
'//FV_A_XZV_OUT/CLOSE_FEEDBACK.CV' = 1
```

Parser output:

```
Parsing expression...
Parsing completed.
Download size = 111 bytes.
```

Figure 12: Parse Test of T3 expression

In performance terms, the system achieved its main operational goal of maintaining continuous filtration while automatically switching between vessels and initiating backwash only when required. The simulation outcomes showed that vessel changeover, trigger response, and alarm handling were executed correctly under both normal and upset conditions. This confirms that the control philosophy moved the system away from static backwash routines toward a performance-driven strategy based on real-time differential pressure. The summary table is shown on Table 2: Simulation of filter fouling and vessel transitions.

Table 2: Simulation of filter fouling and vessel transitions

Time (min)	**DP-A (bar)**	**DP-B (bar)**	**Vessel A State**	**Vessel B State**	**Event**
0	0.32	0.15	IN SERVICE	STANDBY	Normal operation
15	0.55	0.16	IN SERVICE	STANDBY	DP rising
20	0.70	0.18	CHANGEOVER	STARTING	DP ≥ DP_HH
23	0.72	0.20	ISOLATED	IN SERVICE	Flow confirmed
23	0.40	0.22	BACKWASH	IN SERVICE	Reverse wash begins
30	0.18	0.25	STANDBY	IN SERVICE	DP ≤ DP_LL

The operator interface also worked well as it gave a clear view of the state of the modules, the state of the valves, and system transitions. This enhanced operator situational awareness and facilitates effective deployment, as the research was not just interested in the control execution, but also in the way operators can monitor and act on the process using the HMI.

Based on the discussion, the findings show that the proposed system is less prone to fail than fixed or semi-static backwash routines since it reacts directly to actual fouling behavior and not elapsed time per se. This is especially significant when the conditions in the Niger Delta region of Nigeria are considered, where there are many matured wells and the characteristics of produced water are not constant. The paper thus correlates with enhanced backwash control to enhanced continuity of operation, enhanced resistance against reinjection risk, and enhanced use of water and energy resources.

Table 3: Control System Performance Indicators

Metric	Observed Value	Acceptable Range	Status
Controller Scan Time	250 ms	< 500 ms	Acceptable
Communication Errors	0	0	Pass
DP Signal Noise	±0.5 kPa	< ±1 kPa	Acceptable
State Execution Delay	< 1 sec	< 2 sec	Acceptable

4.2 Discussion of Findings

The improved backwash control algorithm transforms the regular filtration operations, which are inflexible and time-based, into a more performance-based, DP-driven approach, so that backwash occurs only when occasional fouling warrants it. This enhances operational stability, eliminates unnecessary cleaning cycles and ensures the quality of reinjected water, which is a critical component to protect injection wells, and minimizes formation damage. The algorithm is most applicable in the Niger Delta where the composition of produced water fluctuates significantly. Its dual-vessel sequencing, interlocking safety, and explicit operator indicators contribute toward uninterrupted flow.

The operator can adjust setpoints based on future real-life data and evaluation of historian trends, this fosters more adaptive operation as time goes by, enhancing the sustainability in the long-term. In general, the results prove that

V. CONCLUSION

This paper demonstrates that differential-pressure–based backwash control provides a more efficient and reliable alternative to conventional time-based filtration systems in produced water reinjection. By initiating backwash only when fouling is detected, the approach reduces unnecessary water and energy use while maintaining consistent effluent quality.

The implementation of a dual-vessel duty/standby system in DeltaV, supported by SFC logic, interlocks, and real-time monitoring, ensured continuous filtration and safe automated operation under varying conditions. The results confirm that differential pressure is a practical indicator for adaptive control, particularly in environments with highly variable produced water characteristics such as the Niger Delta.

Overall, the proposed strategy improves system stability, resource efficiency, and injectivity protection, making it a viable and scalable solution for modern PWRI systems. Further work should focus on field validation and integration of additional process variables to enhance control performance.

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