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APPLIED RESEARCH

A Novel Modular Mobile Power Flow Controller for Real-Time Congestion Management Tested on a 150kV Transmission System

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ABSTRACT Congestion issues are becoming more prevalent as the share of variable renewable energy increases. Conventional methods to mitigate them, such as building new lines, require significant lead time and upfront investment costs. Thus, alternative approaches that deal with congestion problems faster and in a more efficient manner have gained significant interest. In this paper, a modular mobile power flow controller (MPFC) is proposed that can redirect power flow from congested lines to adjacent ones by modifying the line reactance, but also offers additional significant advantages: a) scalability due to the modular nature that allows the MPFC to be sized optimally for addressing specific system needs, b) redeployability due to the mobile deployment method that allows the MPFC to be rapidly deployed and easily removed and redeployed to another location, and c) replicability stemming from the minimal construction requirements for connecting the MPFC to the transmission grid. The whole process of planning, installing, operating and redeploying the MPFC on a 150kV transmission system is thoroughly documented and studied. Overall, this paper presents a novel technology that can offer a quicker and at a lower cost solution to congestion issues, while reducing the impact of new infrastructure on communities and the environment.

INDEX TERMS Power flow controller, congestion, flexible AC transmission systems, power system control.

I. INTRODUCTION

In the past, all the major stages of the power industry, namely generation, transmission and distribution, were controlled by one entity as a vertically integrated utility [1], [2], [3]. However, the electricity industry is undergoing restructuring and deregulation in order to meet increasing demands while maintaining affordable prices and accommodating increased variable renewable energy (VRE) integration [4]. These changes on the electricity industry has on the one hand increased the competition by introducing more stakeholders, but on the other hand, has created a lot of challenges such as network congestions. In particular, demand is satisfied by generators with the lowest cost, no matter their location. This can cause overloading of the transmission lines connecting the generators with the lowest cost [5].

Congestion can refer to an overloading of transmission lines when the thermal bounds are violated and is caused by the physical limitations of the power system [6]. Congestion also occurs when power flows in the transmission line are higher than the flows allowed by operating stability and reliability limits [7]. Voltage limitations in the nodes can also contribute to congestion of the network. Congestion finally can be caused by unexpected contingencies such as equipment failure and generation outages [8]. Overall, the main reason of congestion occurs due

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to the lack of ability to match generation and transmission services.

The European Network of Transmission System Operators for Electricity (ENTSO-E) identified more than 100 bottlenecks in the system which either already exist or are anticipated in the near future [9]. In order to establish a reliable and economical power system operation, it is essential for Transmission Systems Operators (TSOs) to remove congestion issues before any violation of security limits. Generally, two stages of congestion management exist. The first stage takes place before real-time operation, while the second occurs during real-time operation and includes real-time control actions taken from the TSO to manage congestions. Many methods have been suggested for both stages.

For example, for the first stage of congestion management, a congestion risk-aware unit commitment formulation in a two-settlement market environment is presented in [10], which can effectively mitigate the likelihood of transmission congestion in the presence of significant wind power generation. In [11] a control algorithm is developed for congestion management by power flow control using reactance compensation and tested on a 5 bus system. Reference [12] introduces a decentralized transmission line switching in the operation of multi-area power systems to manage congestions both on regional transmission lines and tie lines, while considering credible contingencies. The proposed methodology relies on decentralized optimization methodology. The authors of [13] formulate a unit commitment model that includes generic energy storage and Flexible AC Transmission Systems (FACTS) devices in order to investigate benefits that can be provided from both technologies to the power system, such as reduced congestion. Other works for the first stage of congestion management can be found in [14], [15], [16], [17], and [18].

However, the second stage of congestion management, which includes real-time congestion management, is becoming increasingly important due to the variability and uncertainty of VRE generation. This involves actions taken from the TSO in order to remove real-time occurred congestion and guide the system to a safe operating point. Real-time congestions could occur during unforeseen operation scenarios as well as during outages [19]. There exist cost-free and non-cost free methods for real-time congestion management [20]. The former includes actions such as operation of transformer taps, phase shifters, or FACTS devices, while the later includes generation rescheduling and load shedding [21].

It is obvious that cost free methods are preferred by TSOs for real-time congestion management as they do not increase the generation and operating costs of the power system. These methods mainly include the utilization of FACTS devices. One of the most widely used FACTS devices is the unified power flow controller (UPFC) that is adaptive to various operation conditions for power flow regulation [22]. In [23], the interline power flow controller (IPFC) is examined and it is shown to present great potential for improving the system's performance. In [24] and [25] a static synchronous compensator (STATCOM) device is used for successfully mitigating undesirable operation conditions by injecting suitable reactive powers. STATCOM devices have also been proposed to accommodate renewable generation and microgrid operation [26], [27], [28]. In [29], it is shown that the static synchronous series compensator (SSSC) can change the active power flow on the line it is installed. Moreover, the active power adjustment ability of the SSSC decreases slightly with the increase of the subarea load, but its influence is limited. SSSC devices are also proposed in [30] as a reliable technology solution for enhancing the performance of a system by adjusting different parameters in transmission systems such as the transmission line impedance, the active and reactive powers flow in transmission lines. Thyristor control series compensators (TCSC) have been considered also as an option to reduce curtailed renewable generation as well as investment and generation costs [31], [32]. For further studies in FACTS, the reader can see references [33], [34], [35], [36], [37], and [38].

Among FACTS devices, distributed FACTS (D-FACTS) devices have gained significant interest, since they provide an alternative approach for realizing the full functionality of FACTS devices at lower cost, higher reliability and can be conveniently relocated [39]. The concept of D-FACTS presents great potential for real-time congestion management of a meshed transmission network by routing power flow from overloaded lines to underutilized parts of the network. D-FACTS devices are built in modular fashion and can be installed on transmission towers or in a traditional substation environment. Three main types of D-FACTS exist, namely, distributed static synchronous series compensator (DSSSC), distributed series reactor (DSR), and distributed series impedance (DSI). DSR and DSI devices adjust the impedance of transmission lines, while DSSSC injects a voltage independently of the line current to provide a continuous range of power flow control [40].

In this paper, a novel mobile D-FACTS device is proposed, the mobile power flow controller (MPFC), that utilizes a mobile trailer and can be fully installed and commissioned in a matter of weeks. Such a solution is presented for the first time in literature. This deployment method is quickly deployable (within days), and allows the device to be easily removed and redeployed, enabling system operators to respond to the changing needs of the power network. It presents also additional advantages such as scalability and minimized investment cost. The operation of this novel MPFC is tested and evaluated on an actual 150kV transmission system. It is worth noting that the results usually presented in literature are obtained either from simulation studies or experiments implemented in a scaled prototype. Thus, reporting results from real-time congestion management on an actual transmission system and documenting the planning, installation and operation stages based on field experience, is a valuable input both for TSOs and the research community and provides a reliable validation of the proposed technology. Furthermore, the complete communication and control system architecture that was implemented is described in detail, therefore providing comprehensive information on how this novel MPFC can be operated in practice. Overall, in this work:

1) A novel mobile D-FACTS device solution is presented for real-time congestion management that can be sized optimally for responding to the exact system needs.
2) A detailed description for the implementation of this novel mobile D-FACTS device is provided, including outage scheduling, construction of support structures, preparation of the overhead lines, the actual connection to the grid, and setting up the communication hardware and control system.
3) The ability of this smart technology to enable power lines to dynamically control their power flow based on the real-time needs of the grid is evaluated on a 150kV transmission system. The results of this work provide better understanding of the advantages that the MPFC presents over traditional transmission solutions, such as rapid deployability, scalability and minimized investment cost, and can enable system operators to better manage congestion issues.
4) The redeployability and replicability of the technology is demonstrated by removing and redeploying the MPFC within a short time period to another location.

The rest of the paper is organized as follows. In Section II, the MPFC is described in detail. In Section III an analysis is conducted to determine the line for installing the power flow controller. In Section IV, the whole installation process and steps undertaken are thoroughly described, while real field results are presented in Section V. In Section VI, the redeploybality of the MPFC is showcased followed by a comparison carried out with alternative approaches in Section VII. Finally, some conclusions are drawn in Section VIII.

II. MODULAR MOBILE POWER FLOW CONTROLLER

A. MOTIVATION

The distributed nature and intermittent power output of VRE generation as mentioned before can create issues such as local congestion of transmission lines. Traditional solutions to these issues would involve lengthy reinforcement projects, which can delay or limit renewable generation capacity and can often be very capital intensive. Alternatively, the MPFC can enable better utilisation of the existing capacity on transmission networks, thereby enabling faster connection of renewable generation, lowering constraints and reducing the impact of new infrastructure on communities and the environment. These attributes allow the transition to a low-carbon economy to occur quicker and at a lower cost compared to traditional alternatives.

Overall, the MPFC can:

1) Reduce network congestion and increase system reliability.
2) Integrate renewable energy and reduce curtailment in a cost-effective manner.

FIGURE 1. MPFC trailer solution.

3) Increase utilisation of transmission lines in the near term.
4) Reduce the environmental impact of transmission investments.

B. MODULARITY

The modular nature of the MPFC means that it can be sized optimally for the exact system needs; in turn, this lowers the costs and environmental footprint of the solution by minimising unnecessary use of equipment and space. Additionally, it enables incremental investments in fast timescales thus ensuring scalability and avoids the risk of stranding assets.

C. MOBILITY

D-FACTS devices can be installed on transmission towers or in a traditional substation environment. However, all these deployment methods may limit the redeployability and replicability of the technology, particularly for short-term network needs, since every time specific technical studies must be carried out for the installation. Furthermore, each TSO has different design codes and regulations, thus various installation approaches and physical deployment methods must be selected. In this paper, for the first time a mobile D-FACTS device is presented that uses a containerized solution which is shown in Fig. 1. This method offers rapid deployment and allows the MPFC to be easily removed and redeployed, since it requires minimum construction works, thus dealing with the shortcoming of the previous deployment methods and enabling system operators to address short-term and near-term issues with rapid redeployable solutions.

D. MODULE CONFIGURATION

The power electronics design used for each of the modules that comprise the MPFC is shown in Fig. 2. The number of modules that are implemented in series for each phase in the MPFC depends on the specific system needs. Each MPFC module increases the reactance on the power lines it is installed by injecting magnetizing reactance (X_M) generated by an internal transformer into the lines on command. Each MPFC module is also equipped with two additional current transformers (CTs). The first current transformer (CT_1), is used to harvest a small amount of power from the transmission line to power the control and communications circuits in the modules. The other CT (not shown in detail in Fig. 2)

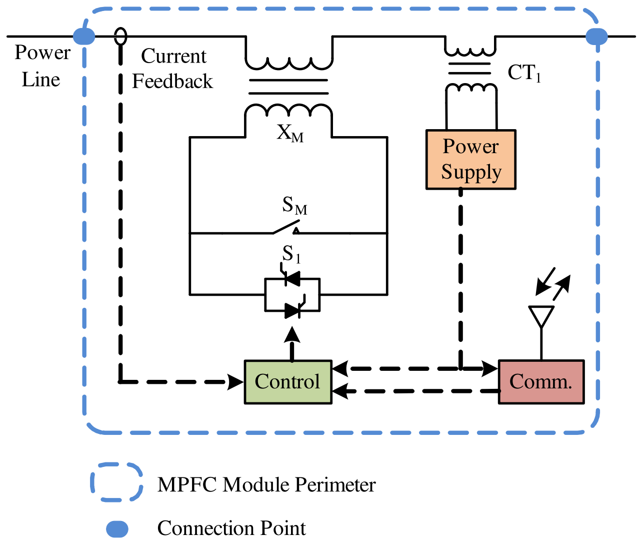

FIGURE 2. MPFC module system diagram.

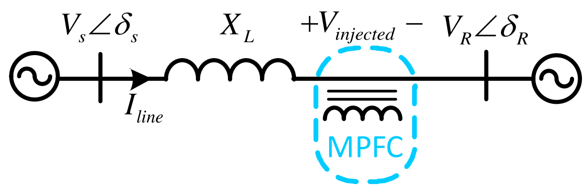

FIGURE 3. Transmission line model with MPFC connected in series.

senses the line current and feeds the measurement into the control circuitry.

The MPFC module offers two distinct modes of operation, with granular performance at each device. Specifically, the two modes are:

- **Injection mode:** the normally-open contactor S_M remains open, and magnetizing reactance X_M is injected into the line. The module rating defines the magnitude of this magnetizing reactance.
- **Monitoring mode:** in this mode the contactor S_M is closed, therefore the reactance coupling transformer is shorted and no reactance is injected into the line.

Whenever the module switches from one mode to another, the antiparallel switches (S_1) are engaged during the short time of contactor state change. This prevents arcing and prolongs the contactor service life. In both modes, the MPFC module is able to transmit telemetry data to the operators. Every unit can be operated independently from the others, achieving various levels of injected reactance. The total amount of reactance injected onto the line by the MPFC depends on the number of MPFC modules in injection mode at any given time. Overall, this kind of light-weight self excited modules can overcome most of the significant issues that have limited a wider deployment of series FACTS devices and are analyzed thoroughly in [41].

A typical transmission line with inductive reactance connecting a sending end voltage source and a receiving end voltage source is shown in Fig. 3 with the MPFC connected in series [42].

In the case we did not have the MPFC, the real power flow P in the transmission line would be given by

$$P = \frac{V_S V_R}{X_L} sin\delta \tag{1}$$

where V_S is the sending end voltage source, V_R is the receiving end voltage source, the power angle δ equals with $\delta = \delta_S - \delta_R$ where δ_S and δ_R are the phase angle of the sending and receiving end voltage source respectively, whereas X_L is the inductive reactance of the transmission line.

The MPFC is capable of emulating a compensating inductive reactance X_M in series with the transmission line. For a given injected voltage $V_{injected}$ by the MPFC, the equivalent reactance equals:

$$X_M = \frac{V_{injected}}{I_{line}} \tag{2}$$

where I_{line} is the line's current.

The expression for the real power flow is then given by

$$P = \frac{V_S V_R}{X_L + X_M\left(1 - S_M\right)} sin\delta \tag{3}$$

where the contactor S_M equals with 0 when open and equals with 1 when closed. The status of the contactor usually is determined by a control strategy that uses the measurement of the line's current and can be described by the following general expression:

$$S_M = f\left(I_{line,measured}\right) \tag{4}$$

To acquire a more accurate model, the different delays τ and disturbances $d\left(t\right)$ could be taken into account as follows:

$$S_M = f\left(I_{line,measured}, \tau, d\left(t\right)\right) \tag{5}$$

Depending on the location of the MPFC and the communication technologies used, the delays τ and disturbances $d\left(t\right)$ would take different values. In the following subsection the control strategies that can be applied on the MPFC are described.

E. CONTROL METHODS

There are mainly two control modes for the MPFC modules [43]. The operator chooses each time which control mode will be implemented in each of the MPFC modules.

- **Manual:** in this control mode, the operator chooses via remote access whether the MPFC module will be operating in injection or monitoring mode.
- **Set-point:** in this control mode, the MPFC module operates autonomously using real-time measurements and predefined thresholds. When the line current exceeds the predefined threshold, then the MPFC switches autonomously from monitoring to injection mode (and

vice-versa). These set-points are defined by the operator. The control strategy is described mathematically in equation (6):

$$S_M = \begin{cases} S_M = 1 & I_{line} < I_{threshold} \\ S_M = 0 & I_{line} \geq I_{threshold} \end{cases} \tag{6}$$

where $I_{threshold}$ is the predefined current threshold.

It should be pointed out that the control methods described can be implemented separately to each of the modules that are included in the MPFC.

As mentioned before the MPFC can sense when the current exceeds a predefined operational limit using a current sensor. For the device to start injecting reactance in order to mitigate the congestion, the control circuit must only give a command to the switch S_M to open (Fig. 2).The coordination with the dispatch center can be done instantly through the TSO's communication network. The delays that are induced in all these procedures (measurements from the sensor, microprocessor commands, communication delays, time duration for the switch to open or close) are in the range of milliseconds, since all are fast electronic procedures.

The coordination of the MPFC with the rest of the power network operation can be carried out both in the day-ahead scheduling as well as during real-time operation. The TSO during the day-ahead scheduling, after simulating the power flows of the transmission system based on load and VRE production forecast as well as power plants generation, can determine the operation of the MPFC in order to achieve an efficient operation of the transmission system. During real-time operation, taking into account the short-term forecast of the power flows and considering also the secondary control actions by the Automatic Generation Control (AGC) that determine the change of the generated unit active power in the range of minutes, the dispatchers in the control center can control the MPFC in order to mitigate possible congestion that can occur in the installed line and adjust efficiently the power flows.

F. PROTECTION OVERVIEW

When the MPFC is deployed on a transmission circuit in injection mode, the line reactance is changed relative to the initial value. During faults, however, all affected MPFC will cease injecting reactance in less than 1ms from the detection of a fault. Relays typically require at least a half cycle (10ms at 50Hz) or more to respond to a fault, greater than the time required by the MPFC to enter monitoring mode (i.e. not injecting) and return the line's reactance to its value without the MPFC. By returning the line to initial reactance without the MPFC injection during faults, the distance relays are not impacted and the initial settings still hold. This is a pivotal property, since the MPFC can be redeployed in different locations without requiring to reconfigure the protection scheme of the TSO each time.

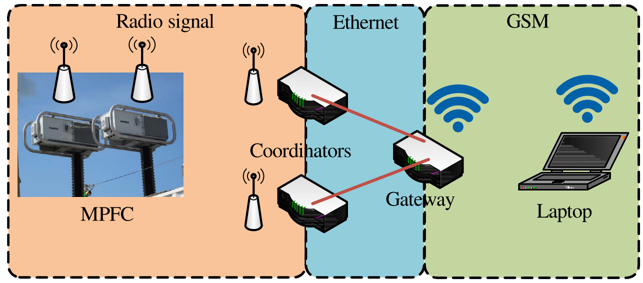

FIGURE 4. Communication system.

G. COMMUNICATION SYSTEM

The communication system is depicted in Fig. 4. Communications between the MPFC modules and the software platform that controls them are first carried out through encrypted radio signals. These frequencies are radio bands reserved for the use of radio frequency energy for industrial, scientific and medical (ISM) purposes other than telecommunications. The ISM signals are then collected by a radio antenna connected to a Coordinator, a device that manages the secure wireless link between the MPFC modules and a Gateway, which provides for operation and management of the MPFC modules and supports multiple communications approaches. The next stage of communications is by secure global system for mobile communications (GSM) signal to a secure website. A laptop device communicates with the secure website through a software program and thereby controls the MPFC modules. Alternatively, the Gateway can directly communicate over a secure channel with the TSO's Energy Management System (EMS). In this case, the operation of the MPFC modules is managed through EMS commands transmitted to the Gateway.

III. LINE SELECTION

Using the PSS/E grid planning software, worst case scenarios are simulated in order to study the power flows in the transmission system using both a current version of the grid, as well as a future version based on the TSO's Ten-Year Development Plan. Through these scenarios, congestion issues can be observed in different lines of the transmission system. Then the MPFC is modeled in these lines (where different number of modules per phase can be examined) and the expected impact on these lines, as well as the adjacent lines, can be assessed.

The Peloponnese region of Greece is currently served solely by a 150kV transmission system. Due to congestion issues, further integration of VRE generation is restricted, while restrictions are also imposed on the operation of a recently built gas-fired power station in the area that could provide much needed flexibility services to the grid. To deal with these problems, an important project included in the Greece's TSO Ten Year Network Development Plan is the expansion of the 400kV grid in the Peloponnese region, via the development of two new line projects. These projects will stimulate renewable energy growth in the region following seven years of stagnation due to lack of network capacity. Furthermore, they will remove operational restrictions imposed on the gas-fired power plant, which is currently operating below nominal capacity. The plant's operation is restricted due to congestion problems under an N-1 contingency.

Based on the PSS/E studies carried out, this operational restriction was indeed verified. However, it was noticed that excess capacity exists on the other nearby transmission lines. Due to sensitivity of information, instead of the actual PSS/E figure, an equivalent diagram shown in Fig. 5 is used. Line 1 connects two substations. In the first one (the one shown in the top of Fig. 5), the gas-fired power plant along with VRE generators are connected, while additionally some other transmission lines are departing (Line 2, Line 3). In the second substation (the one shown in the bottom of Fig. 5), local load is connected. Parallel to Line 1 is another line, when out of service, the overload occurs. Without MPFC deployment, Line 1 is overloaded in a post-contingency scenario, thus imposing operational restrictions to both VRE generators and the gas-fired power plant. Deployment of the MPFC on Line 1 relieves the overload and redirects power to Line 2 and Line 3, therefore increasing utilisation of the transmission system, enabling more renewable generation and mitigating operational restrictions of the power plant. Given this analysis, it was decided to install the MPFC in Line 1.

For this application, each MPFC module was designed to have a reactive power rating of 390 kVAr and a maximum continuous current of 850 A RMS. The minimum reactance that each module can inject is 427mΩ. The maximum emergency current that the module can withstand is 1020 A for a duration of 2 hours. Finally, the maximum fault current is 31 kA for duration of 0.5 sec. The number of modules per phase are chosen appropriately so that the MPFC can alleviate overload and have significant impact on the power flow of the line. In this case, two modules per phase were selected and as shown in the PSS/E simulation studies the MPFC can achieve a significant impact of 17%. Moreover, the transmission line's reactance is comparable to the reactance injected from the MPFC, thereby enabling to get significant results from the MPFC device.

If the MPFC was installed in the other lines, it would also decrease their current value, since by increasing a line's reactance, a part of the power that flows in the line is redirected to adjacent lines. PSS/E studies under different scenarios would show the exact power flows. However, based on the worst case scenarios examined and contingency analysis (N-1), Line 1 presented an interesting use case and thus this line was chosen for the MPFC demonstration.

Based on this line selection, the key operational targets of the MPFC demonstration were: a) to test how much power could be redirected from heavily congested lines to adjacent lines. This excess power capacity that is being "released" could then be potentially used for new renewable generation investments until the planned 400kV line is completed; b) to showcase an alternative way of mitigating the impact of N-1 contingencies in the area, which impose operational restrictions and therefore inadvertently might create market distortions.

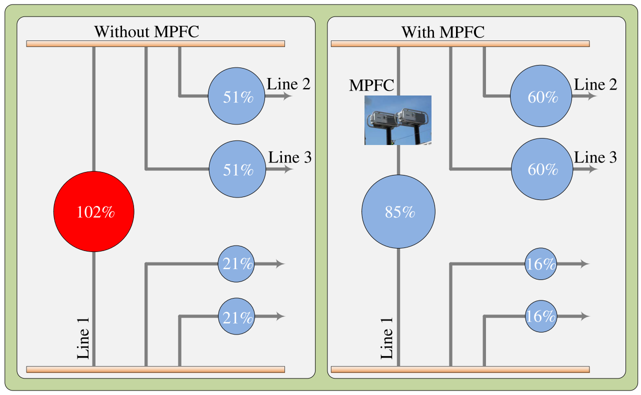

FIGURE 5. Power flow diagram.

When the expansion of the 400kV grid in the Peloponnese region is completed, all the operational restrictions that currently exist will be resolved. Therefore, the MPFC constitutes a very suitable solution, since it will address the near-term issues in the area and then it can be easily removed and redeployed to another location where it is needed.

IV. INSTALLATION PROCESS

Following the selection of a suitable installation line, a complete site survey was conducted in order to determine the optimal deployment site. Based on this survey, the preferred site was chosen to be inside the existing substation on one side of Line 1. Evaluation criteria included site surface materials, slope, configuration of the overhead line conductors, as well as overall site characteristics. Then, all involved parties developed a plan detailing how to connect the MPFC modules (Fig. 6a) to the transmission line and substation ground grid. This installation plan comprised of two major phases; the preparatory work and the final deployment of the MPFC.

In the preparatory phase, concrete bases were built above ground in the substation to accommodate the installation of support poles that will hold the conductors connecting the MPFC modules to the power network. The support structures each comprised a concrete base with a lattice tower structure bolted to the top of it and with a post insulator then mounted on top of the lattice tower as shown in Fig. 6b. Afterwards, during the first outage that lasted two days, insulators were added to the lines in order to "break" them from an electrical perspective and therefore to allow the MPFC modules to be connected to the grid. To maintain the power flow on the lines until the MPFC had been connected, jumpers (small sections of conductors) were attached to the line, externally to the conductors (Fig. 6c). Power flow in the line was restored after completing the preparatory work.

The installation and commissioning phase required approximately 3.5 days. First, the container with the MPFC modules was placed in the predefined location in the

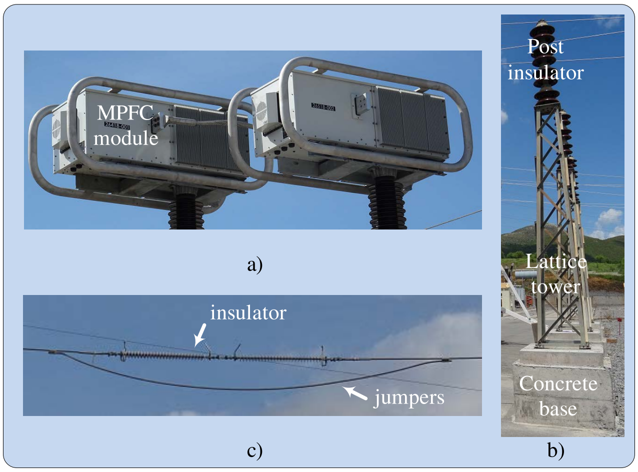

FIGURE 6. a) MPFC modules b) Support structures for the MPFC c) Conductors with insulators and jumpers.

FIGURE 7. MPFC parked inside the substation and four MPFC modules fully elevated to their installation position.

substation between the support structures. Then, the following steps were taken to prepare the MPFC modules for connection to the grid:

1) Remove certain roof panels on the mobile unit (to allow the MPFC modules to be lifted up above roof level);
2) Raise the MPFC modules so that they just protruded slightly above the roof;
3) Bring the insulators that will support the MPFC modules beneath the modules themselves and bolt the two items together;
4) Raise the insulators and MPFC modules into their installation position;
5) Secure the insulators into the appropriate electrical safety clearances position by bolting the support structure used to raise the insulators inside the mobile unit.
6) Attach corona rings and complete the electrical connection between the MPFC modules.

These steps took two days and were completed with the transmission lines in service. In Fig. 7 the mobile container parked inside the substation is depicted, while four MPFC modules are fully elevated to their installation position and two more are protruding slightly above the roof.

After the preparation of the MPFC modules was completed, the connection to the grid was established, which required a $5\frac{1}{2}$ hours outage. A bucket truck was used in the procedure. This time depends mainly on a) spatial and configuration factors of the transmission lines; b) the number of personnel used and their training; c) the tools and machines utilized. Exploiting a larger technical crew with advanced training and modern tools and machines could minimize the time needed for the outage.

Finally, the telecommunications equipment was set up and fine-tuned, which required approximately one more day. Fig. 8 shows the MPFC unit after the installation was completed. Overall, from the above description, the rapid deployment of the proposed novel MPFC is verified.

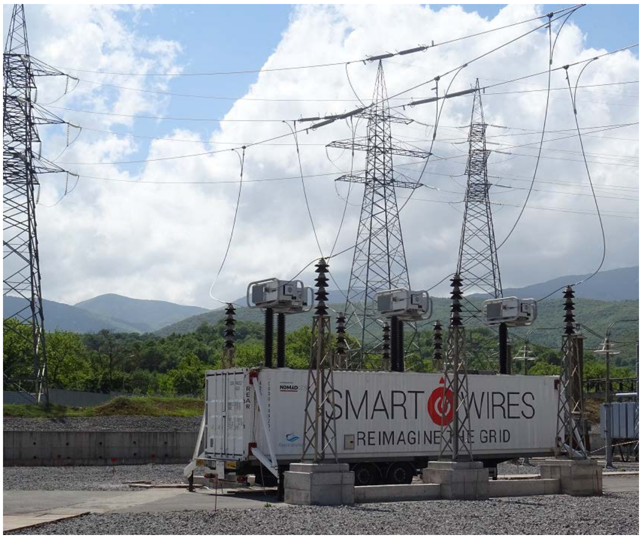

FIGURE 8. Completed installation of the MPFC.

V. REAL FIELD RESULTS

The MPFC performance was tested under different scenarios and evaluated based on measurements obtained both from the MPFC modules sensors as well as from the TSO's Supervisory Control and Data Acquisition (SCADA) system. The MPFC was controlled via a laptop device and was not integrated to the EMS. Results from the two most representative use cases are presented in the following.

A. BASE CASE

In this case, the ability of the MPFC unit to redirect power from Line 1 to adjacent lines under manual operation was tested. First, one MPFC module per phase was set to injection mode, while the other one was kept in monitoring mode. Then, both MPFC modules per phase were set to injection mode. Fig. 9 presents the current measurement obtained directly from the MPFC's sensors, which have a sampling

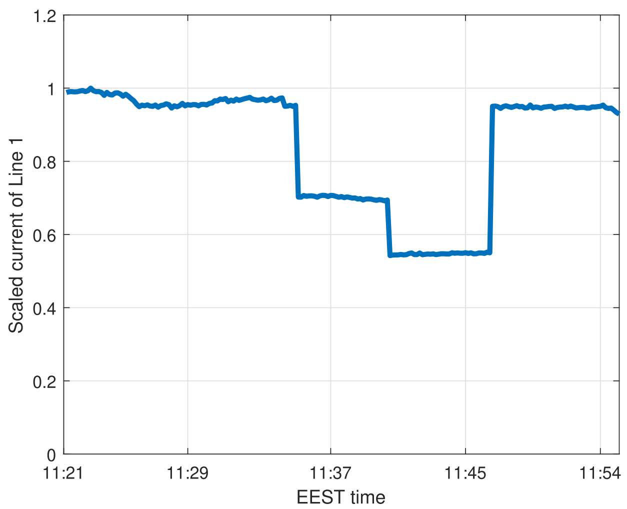

FIGURE 9. Scaled current response in the line on which the MPFC was installed during manual operation.

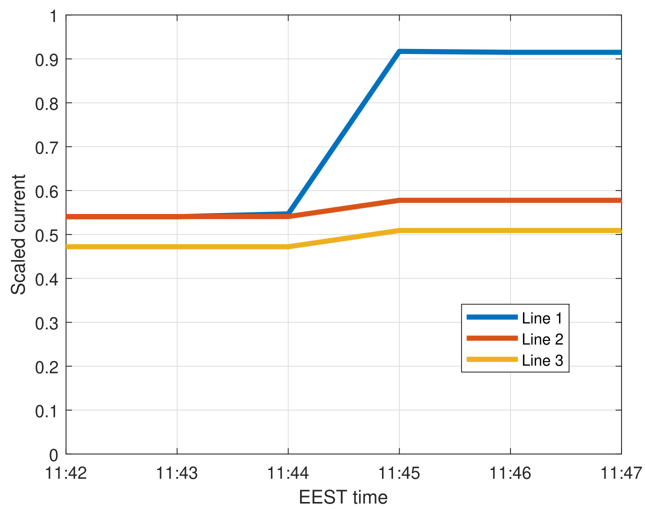

FIGURE 10. Scaled current response of Lines 1, 2 and 3 during a N-1 contingency without the MPFC.

rate of approximately 10 seconds. The line's current is scaled by the maximum current of the presented time frame. The results verify the MPFC's ability to reduce the line current by approximately 25% when one MPFC module per phase is set to injection mode and by more than 40% when both MPFC modules per phase are activated. Overall, the base case confirmed the ability of the MPFC to effectively control the power flow of the line it is installed.

B. N-1 CONTINGENCY CASE

As previously shown in the PSS/E simulation results of Fig. 5, Line 1 becomes overloaded under certain $N-1$ contingency scenarios. To further evaluate this outcome, actual current measurements from the TSO's SCADA system of Lines 1, 2 and 3 scaled by a predefined operational limit are presented in Fig. 10 during a critical outage. One can observe that in this case Line 1 approached very close to the predefined operational limit, whereas the current of Lines 2 and 3 increases slightly. This indicates that the excess capacity of Lines 2 and 3 could be potentially utilized in order to resolve the congestion occurring in Line 1. It should be noted, that the response in Fig. 10 was obtained with the TSO's SCADA system which has a sampling rate of 1 minute and therefore cannot accurately capture the transient response of the currents, giving the false impression that there is a ramp response rather than the actual step response occurring.

To test the ability of the MPFC to mitigate the $N-1$ contingency described above, the set-point control method was implemented. In particular, the predefined operational limit used before was determined as set point for the current. When this set point is reached based on real-time current measurements, then all the MPFC modules are automatically activated and switch from monitoring to injection mode. Fig. 11 displays the current response of Lines 1, 2 and 3 based on measurements from the TSO's SCADA system during the same outage as before. One can observe that the current in Line 1 increases significantly less compared to the case without MPFC, even though the current before the outage happened to be more (63% in to contrast to 54% in the previous case). This is due to the fact that during the outage the set-point was reached and therefore the MPFC modules where automatically activated redirecting the power to adjacent lines. Measurements of the injected reactance per phase from the MPFC unit are depicted in Fig. 12 and confirm that the MPFC modules where in injection mode during the outage. Finally, in Fig. 13 the scaled current of Line 1 measured from the MPFC sensors is shown and is in full agreement with the measurements obtained from the SCADA system. It can be observed that the outage took place sometime between 13:31:41 and 13:31:50 EEST time. Once again, it should be noted, that the response in Fig. 13 was obtained from the MPFC's sensors which have a sampling rate of approximately 10 seconds and therefore cannot accurately capture the transient response of the current, giving the false impression that there is a ramp response rather than the actual step response occurring.

C. EVALUATION OF RESULTS

The two tests that were implemented clearly demonstrate the ability of the MPFC devices to control power flows.

In the first test, stepwise manual operation was implemented whereby the dispatcher selects to inject either 50% or 100% of device's nominal impedance. The MPFC devices reduced power on Line 1 by 29.37% when 50% reactance was applied and by 45.19% when the full 100% reactance was applied. This power was redirected elsewhere, but the aggregate capacity of the network was unchanged. The power flow control activities would allow additional renewable generation to be integrated as well as remove operational restrictions imposed on the gas-fired power plant of the substation. These results are summarized in Table 1.

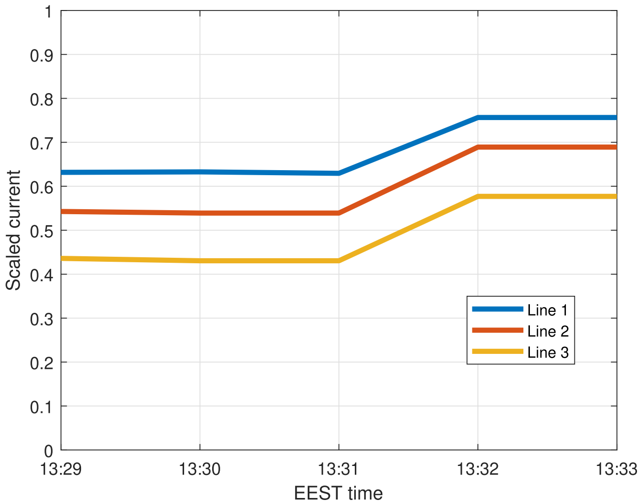

FIGURE 11. Scaled current response of Lines 1, 2 and 3 during a N-1 contingency with the MPFC activated.

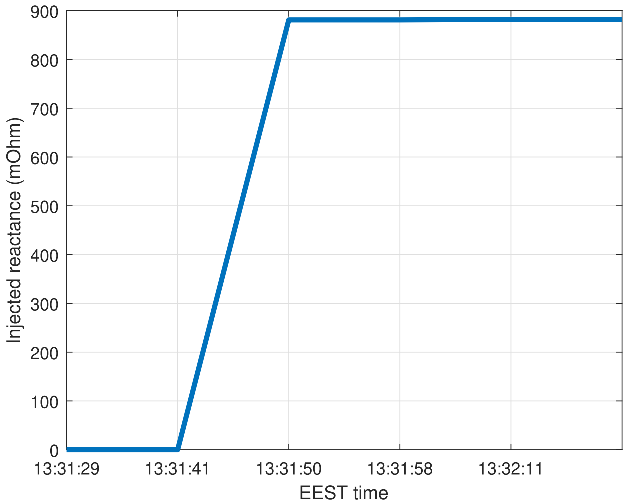

FIGURE 12. Injected reactance per phase from the MPFC.

TABLE 1. Base case results.

Base case	MPFC monitor-ing mode	One MPFC module on Injection mode	Two MPFC modules on Injection mode
Line 1	100%	70.63%	54.81%
Impact on loading		29.37%	45.19%

The second test, the test of automatic operation under an N-1 condition, required only the setting of a current limit on the installation line. The results validated the device's ability to redirect power flows to adjacent lines and effectively mitigate congestion caused by the N-1 event. In this test, the MPFC devices limited on Line 1 the loading by 15.84% that was redirected to Lines 2 and 3 which loading increased by 11.13% and 6.79% respectively. Thus an extra 15.84% additional capacity within the network has been achieved. These results are summarized in Table 2.

These results are very important to TSOs and other stakeholders, as they highlight an alternative way of managing

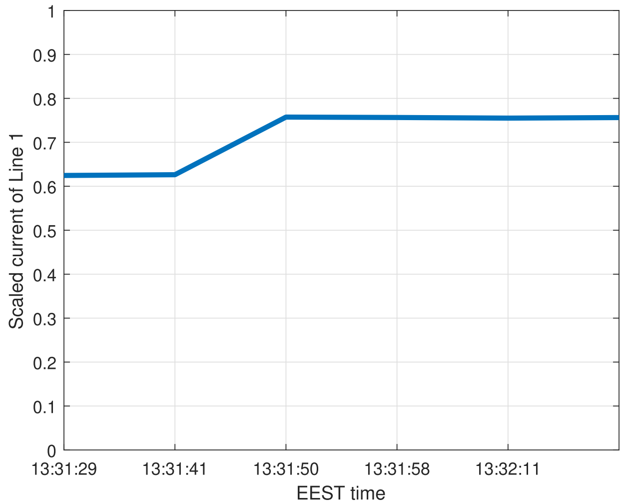

FIGURE 13. Scaled current response of Line 1 as measured from the MPFC sensors during the outage with the MPFC activated.

TABLE 2. N-1 contingency case results.

N-1 congestion	MPFC monitor-ing mode	MPFC Injection mode	Impact on loading
Line 1	91.49%	75.65%	-15.84%
Line 2	57.79%	68.92%	+11.13%
Line 3	50.91%	57.70%	+6.79%

transmission constraints, which requires significantly less lead time and investment when compared to grid expansion and could effectively facilitate higher VRE integration. Given the results of this demonstration, the following could be identified as potential scenarios for installing such a device in the transmission grid:

- Installation of an MPFC device on a line that faces congestion due to high VRE penetration. This is the most straightforward use case and one that allows to directly estimate an amount of VRE capacity added. In such a case, assuming a line faces congestion due to the presence of a number of wind turbines or photovoltaics, installing an MPFC would potentially avoid the need for curtailment during periods of high wind or increased irradiation.
- Installation on an adjacent line that is affected by high VRE penetration. Given the network topology, the case could be that high VRE penetration in one part of the grid could lead to congestion on an adjacent line, which in turn may result in changes in the dispatch schedule. Ultimately, this will result in costlier power plants being in operation thus increasing the overall cost of production. In that case, the MPFC device could be used to ensure that the dispatch schedule is not affected, and the economic operation of the power system is not adversely impacted.
- Addressing N-1 contingency events. As the case in the Peloponnese region, operational restrictions might be imposed due to grid security concerns under N-1 contingency events. Results demonstrated that such events could be effectively mitigated via power flow control.

TABLE 3. MPFC comparison to alternative solutions.

	Series Reactors	Phase Shifting Transformers
Description	• Series reactors increase line reactance and consist of a large wire coil wound around an air-filled or iron core. They can be used to limit fault currents or for power flow control	• Phase shifting transformers control the magnitude and direction of power flow by varying the phase shift across the device
Maintenance Costs	• Low maintenance requirements	• Extensive and costly maintenance required
Ease of Deployment	• Standard equipment familiar to the industry, but must be custom-designed for each application • Fairly easy to install but require large footprint for magnetic clearances	• Standard equipment familiar to the industry, but must be custom-designed for each application • Long-lead time and require substantial substation space
Ability to Redeploy	• Can be re-deployed but only on a line with equivalent or lower voltage and current. Must meet same reactance requirements otherwise it must be scaled in a bulky manner. Civil work represents a large part of the cost and is required every time the asset is moved	• None
Issues	• Lack real-time control and viewed by utilities as a reduction in grid stability • Protection studies and modifications require many months to complete	• Large custom-built substation based devices with logistics challenges • Long lead time required • Maintenance costs associated with frequent switching • Protection studies and modifications require many months to complete
MPFC advantages	• MPFC offers dynamic, granular and real-time power flow control • MPFC bypasses quickly and appears transparent to the protections system • MPFC is rapidly deployed and can be easily redeployed to another location • Solution can be scaled as uncertain need becomes clearer	• MPFC offers granular, real-time power flow control • Can be switched on a sub-second basis with no maintenance costs associated with frequent switching • MPFC avoids the need to perform protection studies and mitigation • MPFC is rapidly deployed and can be easily redeployed to another location • MPFC has low maintenance requirements • Solution can be scaled as uncertain need becomes clearer

- The greater mobility and shorter deployment time enable further use cases that are uniquely suitable for the proposed MPFC such as the following:

Construction Support	Resolving overloads to expand outage windows and accelerating construction of transmission projects
Maintenance Support	Creating or extending outages to enable routine or mission-critical maintenance
Short-Term Congestion	Resolving overloads to reduce congestion that only appears during a limited time period
Transmission Emergencies	Resolving overloads from unexpected challenges arising outside the normal planning process (e.g. unexpected plant closures)
Bridge Solutions	Resolving overloads when permitting or construction is delaying the permanent, long-term solution

Therefore, the installation of a controller could result in a more secure operation and help lift restrictions that might create market distortions, such as in the case of the gas-fired power plant, which is currently operating below nominal capacity.

VI. REDEPLOYABILITY

To demonstrate the redeployability of the proposed solution, the MPFC was removed and was redeployed in the Southern Bulgaria region in order to redirect the active power from a highly loaded/overloaded circuit onto a less utilised circuit,

FIGURE 14. MPFC ready to be transferred to another location.

thereby increasing transfer capacity in the area. A six hour outage was approximately needed to disconnect the MPFC modules from the grid. Then, three more days were required to decommission and remove the MPFC. This work was carried out with the transmission lines in service, thus no outage was required. In Fig. 14, the MPFC is shown fully decommissioned and ready to be transferred to Bulgaria.

VII. COMPARISON WITH ALTERNATIVE APPROACHES

We now compare the performance of the proposed approach with two alternative approaches: a) series reactors [44] b) phase shifting transformers (PSTs) that are considered by ENTSO-E as one of the most economic and reliable approaches for power flow management and system design [45]. Therefore, more thorough conclusions can be drawn concerning the advantages of the MPFC. After running the same simulation scenarios as the one used for the MPFC in Section III, similar results can be obtained with minor differences for both series reactors and PSTs. Nevertheless, the MPFC showcases important advantages that are explained in Table 3. It is clear from the comparison carried out that the main critical points of the proposed design are the scalability due to the modular nature, the redeployability due to the mobile deployment method and the replicability stemming from the minimal construction requirements. Therefore, the MPFC can be considered as an improved solution for any near-term or short-term problem and provides utilities with a critical tool to address the increasingly uncertain needs of the future electric grid.

VIII. CONCLUSION

In this work, a novel modular MPFC is presented and tested in the Greek power system. Using the PSS/E grid planning software, an important operational restriction in the Peloponnese region of Greece was identified. To deal with this constraint, the MPFC was installed on the transmission grid while the appropriate number and ratings of the MPFC modules were selected in order to address the specific system needs (two MPFC modules per phase in this case). The whole installation process and the steps undertaken were thoroughly described proving how quick this technology can be deployed.

To evaluate the MPFC's performance, two representative use cases are presented. First, a stepwise manual operation was implemented. Subsequently, the MPFC was tested in automatic operation under an $N-1$ contingency condition. Results validated the MPFC's ability to redirect power flows to adjacent lines and effectively mitigate congestion. These results highlight that the MPFC offers an alternative way of managing transmission constraints, which requires significantly less lead time and investment when compared to grid expansion as well as lower impact on communities and the environment and could effectively facilitate higher VRE integration. Finally, the MPFC was removed and redeployed in another location in order to demonstrate the redeployability and replicability of this technology.

Overall, in this paper the benefits of the proposed novel mobile D-FACTS design were illustrated and in particular:

- Traditional power flow control solutions can take a number of years to design, manufacture and install, but the proposed MPFC solution can move from design phase to installation in a short number of months.
- With the mobile solution, the installation and commissioning timeframe is as low as two weeks.
- The ability to redeploy the mobile design is also a key characteristic. Redeploying the MPFC will allow transmission owners and operators reuse the investment on multiple lines with different voltages and in different locations on the network. This valuable tool serves as a key asset to transmission owners navigating today's challenges.
- The greater mobility and shorter deployment time enable further use cases that are uniquely suitable for the proposed MPFC such as the following:

Construction Support	Resolving overloads to expand outage windows and accelerating construction of transmission projects
Maintenance Support	Creating or extending outages to enable routine or mission-critical maintenance
Short-Term Congestion	Resolving overloads to reduce congestion that only appears during a limited time period
Transmission Emergencies	Resolving overloads from unexpected challenges arising outside the normal planning process (e.g. unexpected plant closures)
Bridge Solutions	Resolving overloads when permitting or construction is delaying the permanent, long-term solution

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Any opinions, findings and conclusions expressed on this material are those of the authors and do not necessarily reflect those of the host institutions or funders.

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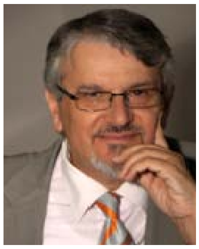

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