Abstract - A control scheme and power management system are proposed for reactive power management in offshore energy producing facilities that includes lengthy submarine cables and variable shunt reactors (VSR). The subject control scheme introduces a new set of operational constraints derived from investigated resonant frequency and transient switching scenarios when operating VSR. These additional constraints are combined with the conventional steady-state load flow acceptable limits to resolve the objective function of voltage management. The proposed control scheme was integrated into an electro-magnetic transient (EMT) model of the energy facilities as part of a project to interconnect offshore platforms at 230kV voltage level, with more than 500km of submarine cables and total of 1480Mvar of distributed VSR. Simulation results proved effectiveness of the method by reducing power quality and switching transient concerns in addition to lowering cable power losses.

Index Terms — variable shunt reactor, reactive power compensation, submarine cable, offshore facilities. Oil and gas.

I. INTRODUCTION

Energy producers are increasing their production from the offshore facilities. Recently, massive submarine cables have been installed to power supply and interconnect offshore producing facilities at 69 kV, 115 kV and 230 kV voltage levels. The power cables have inherited capacitance which increases the voltage level at the offshore facilities during light loading operating conditions. In addition, the cable capacitance introduces damaging switching transients if beyond the equipment withstand capability.

Therefore, design of the electrical system must include voltage management variable shunt reactors (VSR) strategically located to mitigate the cable capacitance overvoltage and damaging switching transients at minimum costs. The paper details a proposed voltage management system for the energy facilities. The voltage management VSR necessitates control scheme to regulate voltage and reactive power while satisfying operational constraints for power quality and reliability.

Several efforts have been reported for offshore reactive power control [2]-[4]. Although their study cases were based on offshore wind generation, the theoretical formulation applies to a certain extent to any offshore power system. References [2] and [4] present reactive power control as a multi-objective optimization problem that mainly minimizes losses while considering typical system constraints for load flow. Likewise, the shunt reactors considered are fixed type, which was the typical approach in legacy designs.

More recently, offshore facilities have reportedly used VSR in their design [5],[6]. The proposed control scheme results in robust reactive and voltage control, the tap selection was constrained to load flow requirements.

The proposed control scheme presented in this paper is based on a multi-objective function optimization problem; that includes not only load flow requirements, but also power quality and switching transient constraints to the optimization problem.

The proposed scheme is integrated into the electro-magnetic transient (EMT) model of the subject case study of over 500km of 230kV submarine cables, generating approximately 2550Mvar capacitive reactive power. Simulation results reflect effectiveness of the method by meeting voltage control objectives, reducing reactive power loading of the system, lowering cable power losses and minimizing power quality and transient switching overvoltages.

The paper also introduces the proposed power management system architecture that will integrate the subject control technique and manage each VSR and power transformer on-load tap changer (OLTC) across the case study of interconnected offshore facilities.

II. VARIABLE SHUNT REACTOR OPERATION

Lengthy submarine cables increase significantly operating voltage due to its inherent capacitance that produces circulating charging current through the system. Fig 1a represents an equivalent circuit of a submarine cable with a shunt reactor connected at the receiving end with the purpose of illustrating the voltage increase per unit length (km) of cable with and without the shunt reactor compensation (Fig 2b).

Note in Fig 2b that without shunt reactor compensation, the effect of cable capacitance can increase operating voltage to damaging levels beyond the cable maximum steady-state limit.
Within shunt reactor compensation technologies, the variable shunt reactors (VSR) are a solution to manage transmission systems. Unlike fixed shunt reactors, these VSR become more cost- and space- effective in systems with high inherited power cable capacitance and wide load variations. Fixed shunt reactors would require several units and switching procedures to regulate voltage while VSR would perform by adjusting online tap charger in accordance to the given operating load.

VSR can interact through control schemes with other regulation devices; such as transformer OLTC, to offer improved control and reactive power management.

The regulation of a variable reactor is accomplished by a separate regulating winding as shown in Fig. 2a. VSRs are typically designed as air core with a regulation range that varies between 50–100% of rated reactive power.

**III. CASE STUDY**

A planned offshore project under execution is used as a case study. The project consists in eight (8) offshore producing platforms that are interconnected to form a multi-terminal offshore power system as shown in Fig. 3.

![Fig. 3. Electrical diagram of the 230kV interconnected offshore facilities for study case.](image)

The cable interconnection system consists of 534 km of submarine cables operating at 230kV. Submarine cable data is shown in Table I.

To manage the reactive power due to these interconnected submarine cables, a number of VSRs have been deployed through in-line and bus connection. Table II shows the data related to the VSR for reactive power compensation and Table III the data for the system sources modeled.

**IV. PROPOSED CONTROL SCHEME**

A. VSR considerations for power quality and switching

In [8] and [9], a detailed discussion is presented for the switching implications of installing large VSR for reactive power compensation.

To the concern of this paper proposal, the specific VSR implications that were used as additional constraints to the objective functions are the compensation close to resonant frequency and delayed zero-crossing switching transient.

The resonant frequency of a compensated line or cable can be calculated as:

\[
\omega_{\text{resonance}} = f \cdot K
\]
being \( f_{\text{resonance}} \) the resonant frequency, \( f \) system frequency and \( K \) compensation factor defined as follows:

\[
K = \frac{\text{Mvar}_{\text{reactor}}}{\text{Mvar}_{\text{cable}}}
\]  

(2)

where \( \text{Mvar}_{\text{reactor}} \) is the reactive power associated to the reactor tap rating while \( \text{Mvar}_{\text{cable}} \) is the submarine cable reactive power derived from its admittance.

### TABLE I
**SUBMARINE CABLE DATA**

<table>
<thead>
<tr>
<th>Branch</th>
<th>Cable length (km)</th>
<th>Cable size (mm²)</th>
<th>Cable reactive power (Mvar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>45</td>
<td>630</td>
<td>147.7909</td>
</tr>
<tr>
<td>2-3</td>
<td>38</td>
<td>630</td>
<td>124.8012</td>
</tr>
<tr>
<td>3-4</td>
<td>50</td>
<td>630</td>
<td>164.2121</td>
</tr>
<tr>
<td>4-5</td>
<td>30</td>
<td>1000</td>
<td>250.8473</td>
</tr>
<tr>
<td>ckt1=ckt2</td>
<td>60</td>
<td>630</td>
<td>442.8773</td>
</tr>
<tr>
<td>3-6</td>
<td>13</td>
<td>630</td>
<td>42.6951</td>
</tr>
<tr>
<td>3-8</td>
<td>6</td>
<td>630</td>
<td>19.7055</td>
</tr>
<tr>
<td>6-7</td>
<td>10</td>
<td>630</td>
<td>32.8424</td>
</tr>
<tr>
<td>8-9</td>
<td>14</td>
<td>630</td>
<td>45.9794</td>
</tr>
<tr>
<td>9-10</td>
<td>11</td>
<td>630</td>
<td>36.1267</td>
</tr>
<tr>
<td>7-10</td>
<td>15</td>
<td>630</td>
<td>49.2636</td>
</tr>
<tr>
<td>10-11</td>
<td>76</td>
<td>630</td>
<td>249.6024</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>2550.0709</td>
</tr>
</tbody>
</table>

### TABLE II
**VSR DATA**

<table>
<thead>
<tr>
<th>Bus</th>
<th>VSR size (Mvar)</th>
<th>Connection type</th>
<th>Regulation range</th>
<th>Regulation step</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>80</td>
<td>1xIn-line</td>
<td>50-100%</td>
<td>Non-linear,&lt;3%</td>
</tr>
<tr>
<td>3</td>
<td>2x120</td>
<td>2xIn-line</td>
<td>50-100%</td>
<td>Non-linear,&lt;3%</td>
</tr>
<tr>
<td>4</td>
<td>2x120</td>
<td>2xIn-line</td>
<td>50-100%</td>
<td>Non-linear,&lt;3%</td>
</tr>
<tr>
<td>5</td>
<td>2x123</td>
<td>2xIn-line</td>
<td>50-100%</td>
<td>Non-linear,&lt;3%</td>
</tr>
<tr>
<td>10</td>
<td>2x120</td>
<td>2xIn-line</td>
<td>50-100%</td>
<td>Non-linear,&lt;3%</td>
</tr>
<tr>
<td>11</td>
<td>1x95</td>
<td>2xIn-line</td>
<td>50-100%</td>
<td>Non-linear,&lt;3%</td>
</tr>
<tr>
<td>Total</td>
<td>1482</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### TABLE III
**SOURCE MODELING**

<table>
<thead>
<tr>
<th>Source</th>
<th>Voltage (kV)</th>
<th>Positive sequence impedance (( \Omega \angle ))</th>
<th>Zero sequence impedance (( \Omega \angle ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>230</td>
<td>15.625\angle 87.5°</td>
<td>9.472\angle 85.39°</td>
</tr>
<tr>
<td>2</td>
<td>230</td>
<td>35.563\angle 87.59°</td>
<td>9.776\angle 86.55°</td>
</tr>
</tbody>
</table>

When the cable admittance MVAR is 100% compensated by the shunt reactor tap, the current circulating through the subject cable experiences high values of negative- and zero-sequence currents due to the shunt resonance. This results in undesired power quality issues at the receiving end.

For the provided study case, the resonant frequency has been studied for different combinations of VSR tap positions across the interconnected facilities to capture the conditions that potentially trigger resonance.

The other aspect is the VSR transient switching that might result in current waveform missing zero crossing. This transient, if occurs during trip or open command in an AC interrupting device, can potentially lead to breaker failure and further aggravate system restoration and downtime. The resolution is to ensure a compensation factor using (2) less than 50% at the moment of energization, or to remove VSR to the possible extent from the receiving end if resulted in a radially-fed system configuration. More countermeasures for this delayed zero-crossing phenomenon is discussed in [7].

### B. Initial reactive power compensation estimation

The initial reactive power compensation factor (2) and VSR tapping is obtained through an optimization formulation function to minimize power losses as follows:

\[
\text{Min} \ f(x) = \sum_{i,j} \left( \text{P}_{\text{loss,R}_{\text{ij}}} + \text{P}_{\text{loss,Z}_{\text{ij}}} \right) = \sum_{i,j} \left( G_{ij} \cdot (U_{i}^2 + U_{j}^2 - 2 \cdot U_{i} \cdot U_{j} \cdot \cos(\theta_{i} - \theta_{j})) \right)
\]

\[i, j \in \text{branch between two nodes}\]

(3)

being \( G_{ij} \) the conductance between nodes \( i \) and \( j \), \( U_{i} \) and \( \theta_{i} \) are voltage phasor magnitude and phase angle at node \( i \). Here, the independent variables \( x \) is the reactance of each VSR in each node \( i \).

The optimization is conducted by using the conventional load flow constraints [10] in addition to the resonant frequency and current zero missing as follows:

\[
\text{Mvar}_{\text{VSR,R}} + \text{Mvar}_{\text{VSR,Z}} = \sum_{i} \left( \frac{1}{2} \cdot \left( \text{P}_{\text{VSR,R}_{\text{ij}}} + \text{P}_{\text{VSR,Z}_{\text{ij}}} \right) \right)
\]

(4)

\[
\sum_{i,j} \left( \frac{1}{2} \cdot \left( \text{Mvar}_{\text{VSR,R}_{\text{ij}}} + \text{Mvar}_{\text{VSR,Z}_{\text{ij}}} \right) \right)
\]

(5)

where (4) constraints the individual branches to compensate at resonant frequency, which is impedance-based phenomenon, while (5) imposes both integral and circuit segments, the constraint does not compensate the offshore system beyond 85% of cable actual reactive power, which leads to transient switching concerns including current zero missing. The subject objective function with its constraints is resolved by using optimization toolbox of the EMT software.

### C. Reactive power compensation control scheme

After objective function is solved and initial VSR taps are in operation, the second stage of the control scheme starts by determining if measured voltages at each bus are within the load flow requirement. When a given bus voltage deviates outside its threshold, the proposed scheme initiates the voltage regulation by...
anticipating the taps required for mitigation, and if it requires further support from adjacent VSR. To accomplish this feature, the influence of a single tap of pair of VSRs over the corresponding sending and receiving end bus voltage has been computed for each submarine cable branch.

Unlike some literature, installed VSR regulation steps are non-linear as shown in Fig. 4. Accordingly, an exponential function (6) has been determined to improve control scheme estimation of number of taps required for voltage regulation:

\[
\text{Regulation(TAP)} = 0.0119 \cdot e^{0.0492 \cdot \text{TAP#}}
\]  

Fig. 4. Approximations function to the installed VSR non-linear regulation steps.

The relation between voltage variation and VSR tap regulation is computed at each bus. Therefore, each bus VSR capability to regulate its voltage within the target threshold is assessed as follows:

\[
U_{\text{comp},i} \cdot \sum_{n} (VSR_{\text{tot,Mvar}} - VSR_{\text{tap,n}}) \geq U_i - U_{\text{ref}}
\]

being \(U_{\text{comp},i}\), the respective bus \(i\) voltage compensation per connected VSR regulation step, in kV/Mvar, \(VSR_{\text{tot,Mvar}}\) the total size of connected \(n\) VSR to bus \(i\), \(VSR_{\text{tap}}\) the estimated actual tap reactive power of connected \(n\) VSR to bus \(i\).

This assessment and subsequent controller actions are simplified in Fig. 5 flowchart.

I. SIMULATION RESULTS

The proposed control scheme has been integrated in the electro model for the offshore interconnected system depicted in Fig. 3.

The advantage of the proposed scheme is highlighted in those scenarios in which VSR - at a given bus - has reached its maximum tap, and therefore, provided (5) is satisfied, a tap operation command is shared to adjacent VSR, or otherwise, a system reconfiguration is executed. For simplicity of results discussion, Sub-05 to Sub-06 subsystem is isolated and not considered in the simulation results.

![Fig. 5. Proposed reactive power compensation control scheme.](image-url)
In Fig. 7 the scenario of a load rejection of 100MW is simulated to analyze the control scheme implication at voltage regulation and stability. Note that (7) calculation determined that local capacity for Mvar absorption is no longer sufficient for the new voltage increase, and therefore, a remote compensation signal is activated, as observed in Fig. 7b to adjacent VSR at bus-2 and bus-10 to increase their tap despite having bus voltage within acceptable limits.

Unlike power transformer OLTC, the VSR regulation step influence over the voltage magnitude is relatively small and goes undetected due to the same AVR measurement error tolerances.

If instead of 100MW, a 150MW of load rejection is simulated, the control scheme will be constrained by two requirements; (5) that anticipates switching issues due to heavily compensated system, and for (7) that available local and remote taps are not sufficient to regulate voltage increases back to required limits. Therefore, an action is initiated to isolate the 14km of submarine cables between buses 8-9. Fig. 8 shows the simulation results for this scenario, which can be equally considered as a lightly loaded operating condition.

The architecture for the proposed variable shunt reactor control scheme consists of a main controller duplicated in two different locations; onshore and offshore, to provide the calculation engine and core functions of the control scheme. The architecture is complemented with the auxiliary devices that provide peripheral functions such as metering and equipment status data.

Front-end processors (FEP) will interface with the field devices I/O modules and PSA gateways to gather required data. This information from the FEPs is then sent to the main controller for computation and decision-making.

Fig. 9 illustrates a simplified data flow diagram with physical device locations and communication media channels. All fiber-optic-based devices are communicated through Ethernet switches.
For redundancy purposes, all FEPs will have redundant connections with the main controller in both onshore and offshore. PSA gateways will have hot redundancy, and main controller will have a hot-standby redundancy.

For redundancy purposes, all FEPs will have redundant connections with the main controller in both onshore and offshore. PSA gateways will have hot redundancy, and main controller will have a hot-standby redundancy.

**III. CONCLUSIONS**

Variable shunt reactors enable voltage regulation for a wide range of load variation; however, additional steady-state operational constraints are needed to avoid transient switching concerns and operation under resonant frequency.

Due to its small voltage compensation per regulation step, VSRs are exposed to a high number of tap changer operations. Therefore, tap step should be desirably designed for each specific project to optimize number of taps per compensation requirement.

A power management system for reactive power compensation of interconnected systems maximizes voltage controllability by utilizing adjacent compensation devices to support a given local demand.

**IV. REFERENCES**


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