Improved Coordinated Control Strategy for Hybrid STATCOM Using Required Reactive Power Estimation Method

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ABSTRACT The penetration level of renewable energy resources has grown in such a way that their effects on the power system can no longer be neglected. In order to cope with these problems, grid operators are forced to improve the stability of the grid connection point, and the static synchronous compensator (STATCOM), which has a fast dynamic response is emerging as an alternative. Due to the prohibitive cost of STATCOM, however, grid operators have begun applying a new concept of hybrid STATCOM, which is a combination of mechanically switched capacitors (MSCs) and STATCOM. Thus, this paper investigates the use of new coordinated control between STATCOM and MSCs, and the solution relies on the required reactive power estimation method using online grid strength level (OGSL) index, which is newly proposed in this paper, and the optimal MSCs allocation algorithm. Following the proposed procedure, an improved coordinated control scheme is obtained whose objective is to reduce the switching times of the MSCs while maximizing the reserve reactive power margin of the STATCOM in transient state. This proposal is analyzed on the Jeju island power system in South Korea with the developed hybrid STATCOM model.

INDEX TERMS Hybrid STATCOM, MSCs, online grid strength estimation, coordinated control.

NOMENCLATURE

P_{st}	Active power output of STATCOM
Q_{st}	Reactive power output of STATCOM
U_{pcc}	PCC bus voltage magnitude
E_{st}	STATCOM bus voltage magnitude
$U_{dc,ref}$	Reference dc voltage of STATCOM controller
$U_{dc,mes}$	Measured dc voltage of STATCOM controller
P_{mes}	Measured active power
Q_{mes}	Measured reactive power
U_{mes}	Measured voltage at PCC
$U_{pcc,ref}$	Reference voltage of STATCOM controller
w	Rotational speed
w_{ref}	Reference rotational speed
φ	Angle of rotation
δ_1	PCC bus voltage angle
δ_2	STATCOM bus voltage angle
b_{st}	Susceptance between PCC and STATCOM bus
U_d	d-axis voltage
i_d	d-axis current
U_q	q-axis voltage
i_q	q-axis current
$Q_{msc,x}$	Reactive power output of xth MSC
$b_{msc,x}$	Susceptance of xth MSC
$Q_{Hybrid,st}$	Reactive power output of Hybrid STATCOM
U_{change}	User defined PCC bus voltage variation
U_{max}	PCC bus voltage upper limit
U_{min}	PCC bus voltage lower limit
$Q_{Required}$	Required reactive power at PCC bus
l	Number of MSCs
D_x	Droop coefficient of xth MSC
T	Time constant
k_p	Proportional gain
k_i	Integral gain
I_{max}	VSC output current upper limit
I_{min}	VSC output current lower limit

I_{total}	Total current output of Hybrid STATCOM
S_τ, τ_{dip}	Voltage dip time duration
S_v, V_{dip}	Voltage dip magnitude

I. INTRODUCTION

In the grid planning and operation of a stressed power system due to a high level of renewable energy penetration, the ability to maintain a stable voltage has become a growing concern. Since power transfer limitations have frequently been observed due to reactive power unbalances and load change, grid operators have tried to apply high-voltage, high-current power electronic devices like static synchronous compensator (STATCOM) [1], static var compensator (SVC) [2], thyristor controlled series capacitor (TCSC) [3] and unified power flow controllers (UPFC) [4] into the power system. The main advantages of these flexible ac transmission systems (FACTS) solutions are their rapid dynamic response [5], frequent variations in output, and ability to maintain grid stability and grid code [6], [7].

In the operation of FACTS, it is desirable to have a systematic and efficient tool to investigate how FACTS can impact the operation of the whole system. Sensitivity analysis is often used for this purpose, because it sets up a direct analytical relation between the control variables and observed variables. Such relations based on direct and indirect methodologies were well represented in [8]–[11]. Also, the previous studies related to design a robust damping controller shows effective performance for a range of operating conditions of the nonlinear power system [12], [13], and some papers share the modeling knowledge for control application [14]–[16]. However, this increasing rate of the FACTS device has given rise to concerns about cost efficiency for grid operators since a FACTS device requires a large initial capital outlay; thus, the application of one of the several devices should be cost-effective. For this reason, the Hybrid STATCOM system, which is a combination of STATCOM and another Var compensation device to reduce STATCOM capacity, has been introduced [17].

Up to now, several global heavy electrical corporations have actively developed their own Hybrid system, and operation schemes [14], [18]–[21]. The notable one is the San Diego Gas & Electric system for dynamic Var control during peak load condition [19]. This system control has a function of keeping the output of the reactive power to a minimum value, and if the reactive power from STATCOM is outside a deadband for a specified time, a control signal connects or disconnects the capacitors. As another project, the Holly STATCOM in Austin, Texas, which is based on ABB (ASEA Brown Boveri)'s SVC Light platform, is combined with two kinds of 31.2Mvar capacitor banks, and it utilizes the MACH2 control system, a common control platform used for all ABB FACTS and HVDC Projects [20]. The controller inherently has the capability to automatically take actions for switching in and out the three 138kV Mechanically Switched

Capacitors (MSCs). Similarly, another SVC Light was operated to cope with the severe flicker mitigation demands in RWE Energie, Europe [21].

In the literature side, some authors have presented enhanced transient state control of Hybrid STATCOM [22], [23]. In steady state, STATCOM is adjusted to absorb as much reactive power as possible, so it is able to provide more reactive power in post-fault transient state. The improved PI (Proportional and Integral) control of STATCOM can further increase the reactive power output and improve the short-term voltage stability.

In mentioned papers and various projects, however, there has been no descriptions as to which capacitors are switched on or off at certain times. It is an important issue that MSCs are composed of several different capacities, and its frequent switching to deal with power quality issues may even cause resonance and transient overvoltage [24]. Furthermore, the number of switching times impacts the stresses on the life cycle of passive devices, exact switching on and off is important. In this paper, therefore, the passive Var compensation device of MSCs was combined with the STATCOM, and novel coordinated control strategy was suggested. The main task of proposed strategy is to reduce the switching times of MSCs, while increasing the reserve reactive power margin of STATCOM. To do this, both required reactive power estimation method with developed index and optimal allocation algorithm of MSCs are suggested in this paper, respectively.

This paper is organized as follows, the basic Hybrid STATCOM model is introduced in Section 2. In Section 3, the improved coordinated control strategy and optimal MSCs allocation algorithm using developed Hybrid STATCOM model in PSS®E (Power Transmission System Planning Software) environment are introduced, respectively. Lastly, a simulation of the model with the proposed control scheme is illustrated in Section 4.

II. HYBRID STATCOM MODEL CONFIGURATION

Based on Voltage Source Converter (VSC) and Insulated Gate Bipolar Transistor (IGBT) technology, the STATCOM is capable of yielding a high reactive input to the grid. The function is to be a fully controllable voltage source matching the system voltage in phase and frequency, with an amplitude which can be continuously and rapidly controlled, so as to be used as the main tool for reactive power control. The active and reactive output of VSC based STATCOM are as follows:

$$P_{st} = b_{st} U_{pcc} E_{st} j sin(\delta_1 - \delta_2), \tag{1}$$

$$Q_{st} = j b_{st} \left[U_{pcc}^2 - U_{pcc} E_{st} \left[cos(\delta_1 - \delta_2) \right] \right]. \tag{2}$$

where U_{pcc} and E_{st} are the voltage of PCC (Point of Common Coupling) and the STATCOM bus, respectively, and b_{st} is the susceptance between two buses as shown in Fig. 1. The $\delta_1 - \delta_2$ is the phase difference between two voltages. From (1) and (2), in choosing a zero-phase shift between U_{pcc} and E_{st},
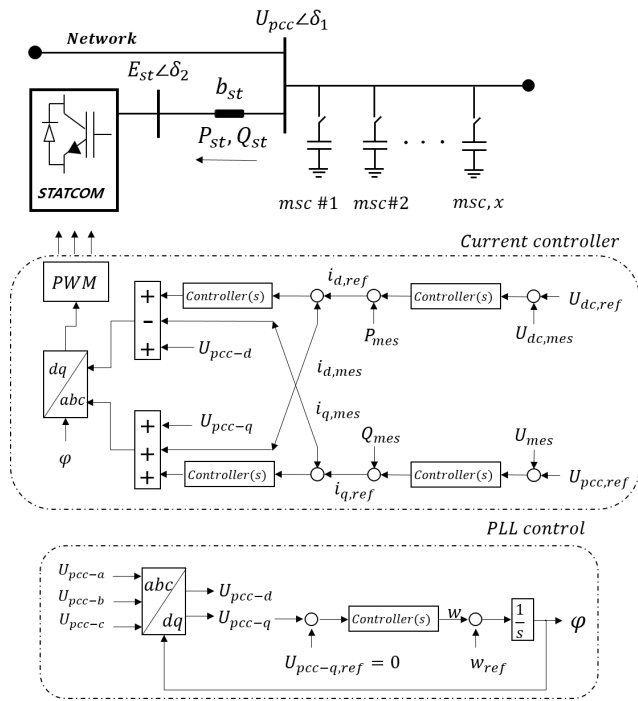
FIGURE 1. Simplified diagram of hybrid STATCOM.

the system will act as a purely reactive compensation source assuming there is no losses.

For the STATCOM controller modeling, the widely used vector control is applied as shown in Fig.1. Let the STATCOM side impedance be simply modeled as a series-connected three phase impedance, and the reference voltage generated by the inner current control loop is transformed back into the *abc* frame and used for pulse with modulation (PWM) to produce the desired converter three-phase voltage. For determining stable controller parameters, the PWM switching delay is then approximated by a first-order Pad é approximation, and impedance based stability analysis has to be performed [25], [26]. The *q*-axis current of the *d-q* frame is aligned with the ac system phasor based on PLL, i.e., $i_q = 0$, therefore, dc & ac voltage and droop control can be achieved through (3) and (4).

$$P_{st} = \frac{3}{2} v_d i_d, \tag{3}$$

$$Q_{st} = -\frac{3}{2} v_d i_q. \tag{4}$$

Notable one is that the prolonged voltage oscillation at the lowest resonant frequency results oscillations on the dc side that the appropriate control parameters should be chosen [25], [26]. Especially, the PLL gain or integral term of ac voltage controller should carefully be chosen.

On the other hand, the dynamics of MSCs related to connection and disconnection requires some response delay time due to a mechanical characteristic. The reactive current depends on the grid voltage, and the reactive power decreased with the square of the grid voltage consequently as

shown in (5).

$$Q_{msc,x} = b_{msc,x} \times U_{pcc}^2. \tag{5}$$

where $Q_{msc,x}$ refers the output reactive power at *x*th MSC, and $b_{msc,x}$ is the susceptance of *x*th MSC. From a dynamic point of view, each connection or disconnection causes voltage and current variation due to the step variation of the reactive power. By combining with MSCs, the dynamic support range could be more improved than the only STATCOM system, and this combination provides better capability to voltage regulation. The reactive power capability of Hybrid STATCOM can be written as:

$$Q_{st}^{Min} \leq Q_{Hybrid,st} \leq \sum_{x=1}^{l} Q_{msc,x} + Q_{st}^{Max}. \tag{6}$$

where *l* means the maximum number of installed MSCs, and Q_{st}^{Min} and Q_{st}^{Max} represent maximum inductive and capacitive region of STATCOM, respectively. And to configure the modified controller model, two functions for improved coordinated control are included: The required reactive power estimation method, and the optimal allocation algorithm of MSCs. The detailed descriptions are represented hereafter.

A. REQUIRED REACTIVE POWER ESTIMATION USING OGSL INDEX

To perform an optimal MSCs allocation, the required reactive power from the grid has to be estimated online at the side of the Hybrid STATCOM. However, the grid status is always changed, even within a single day, due to uncertain combination of supply and demand side as shown in Fig. 2. Especially, the system response to such a contingency event is further complicated when system loads include a high content of induction machines, as the reactive demand of such loads is very high at fault clearing because of the deceleration of the machines during the fault. It makes difficult how much reactive power can compensate the certain voltage drop.
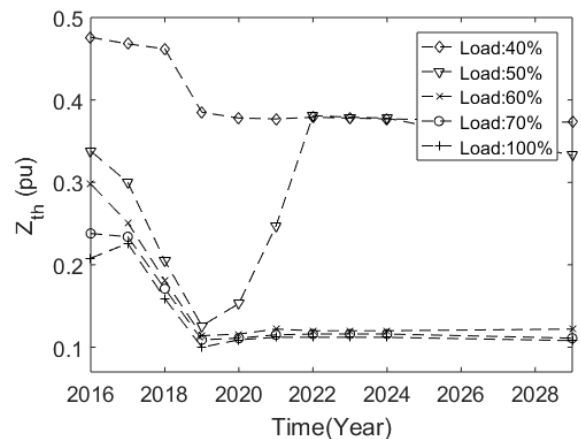

FIGURE 2. Equivalent impedance change depending on load condition at hybrid STATCOM bus in each year.

Thus, we need to track a grid strength online. In order to estimate the changing grid robustness, the novel index

as *Online Grid Strength Level (OGSL)* is newly applied in this paper. Based on (7), the ac voltage reference change for STATCOM versus reactive power output decides the *OGSL* level. For the same voltage reference change, if the variation of Q_{st} is large, the grid has a high robustness level. On the other hand, if the variation of Q_{st} is small, the grid has a small strength level.

$$OGSL\left(Mvar\big/pu\right) = \frac{dQ_{st}}{dU_{pcc}}. \qquad (7)$$

As a result, the reactive power output according to $U_{pcc.ref}$ changes from one stable state to another stable state depending upon the grid topology or load level. This process provides an attractive advantage that required reactive power amount can be estimated at each time frame, which differs from the several existing grid strength indices. Furthermore, this control protocol does not require additional communication equipment like phasor measurement units. Note that the control response time varies with each STATCOM, the discrete time representation which is the interval time to reach another stable state is applied, while achieving smoothing of index. It is generally set in seconds. The *OGSL* at the kth instant can be determined suing the following expression:

$$OGSL\,(k)$$
$$= S \times \left[\frac{Q_{st}\,(k) - Q_{st}\,(k-1)}{U_{change}\,(k) - U_{change}\,(k-1)}\right], \qquad (8)$$

$$S = \begin{cases} 0, & if\ U_{min}(k) > U_{pcc,mes}(k)\ or\ U_{mes}(k) > U_{max}(k) \\ 1, & if\ U_{min}(k) \le U_{pcc,mes}(k) \le U_{max}(k) \end{cases} \qquad (9)$$

where, Q_{st} is the measured variable of STATCOM and the STATCOM continuously changes by adding or subtracting additional voltage reference as U_{change} to estimate *OGSL* index. However, $U_{pcc,ref} \pm U_{change}$ term should not affect the system reliability standard, therefore, the term should have a specific dead-band as $U_{min} < U_{pcc,ref} \pm U_{change} < U_{max}$ based on each country grid code. In this paper, $U_{pcc,ref}$ and U_{change} were chosen as 1.02pu and 0.005pu, respectively. Furthermore, by observing (8), it is apparent that the STATCOM will continuously be governed by the U_{change} even though the contingency event occurs. Hence, the S term separates the *OGSL* estimation period and the contingency event period based on (9). If the measuring voltage as $U_{mes}(k)$ is smaller than $U_{min}(k)$, which represents the minimum allowable voltage point at PCC, the STATCOM recognizes whether or not there is a fault. In other words, if at any time due to any system disturbance, the bus voltage violates the utility specified limit, the binary signal as S is switched to 0 and *OGSL* estimation period is over. The voltage control is then activated utilizing reactive power exchange up to the full STATCOM capacity. If the voltage is successfully regulated to within the utility specified range, the estimation mode ($S = 1$) is performed again. In conclusion, the *OGSL* index is continuously updated at the Hybrid STATCOM side, and the system determines itself about the grid status.

Using the *OGSL* index, the required reactive power amount at kth time can be calculated using (10). The values of ΔU_{change}, ΔQ_{st}, $U_{pcc,ref}$ and $U_{pcc,mes}$ are all known values through (8); thus, the required reactive power amount as $Q_{required}$ can be calculated as follows:

$$Q_{required} = \frac{\Delta Q_{st} \times \left(U_{pcc,ref} - U_{pcc,mes}\right)}{\Delta U_{change}}. \qquad (10)$$

If the $Q_{required}$ is calculated as larger, it can be assumed that the grid has a high value of *OGSL* at kth time; On the other hand, if the $Q_{required}$ is estimated as smaller, it can be assumed that the grid has a low strength level.

B. OPTIMAL ALLOCATION ALGORITHM OF MSCs

After the $Q_{required}$ calculation, the optimal MSCs allocation procedure is performed. A detailed description is hereafter.

1. The $Q_{msc,x}$ is recalculated based on the grid voltage at kth time. By using their droop characteristic, the compensation amount was recalculated based on (11).

$$Q_{msc,x}\,(k) = Q_{msc,x}\,(k) - U_{mes}\,(k)\,\frac{U_{pcc,ref} - U_{pcc,mes}\,(k)}{D_x \times U_{pcc,ref}}. \qquad (11)$$

where D_x, as $x \to l$ is the droop slope of xth MSC, which is clearly tied to the relation in (5).

2. If the $Q_{required}$ is larger than $\sum_{x=1}^{l} Q_{msc,x}(k) + Q_{st}^{Max}(k)$, while maximum current as I_{st} from STATCOM is sustained for t_{block} times, all MSCs are turned on.

3. If the $Q_{required}$ is smaller than $\sum_{x=1}^{l} Q_{msc,x}(k) + Q_{st}^{Max}(k)$, while the current from STATCOM is sustained for t_{block} times, the STATCOM decreases its reactive power to zero (This process is defined as a "*Q margin securement control*"). Then, the xth MSC which satisfies the equation of $min\left\{Q_{required}(k) - \sum_{x=1}^{l} Q_{msc,x}(k)\right\}$ are turned on.

By combining the $Q_{required}$ result and optimal allocation algorithm, the simplified control block diagram of the proposed coordinated control is presented in Fig. 3, and the main advantages of the proposed method comparing to step by step turn on logic are as follows:

- Since the required reactive power amount is injected into the grid at once, more rapid and exact dynamic compensation is possible. In the conventional operation strategy, however, the MSCs are turned on one by one because the operators should observe how much the voltage changes after a certain MSC input. Therefore, if the voltage is not recovered, the operator turns on the remaining MSCs, which has a mechanical time delays.

- The correct on and off signal prevents unnecessary operation of MSCs, and this can improve the life cycle of devices.

- The reserve reactive power margin for STATCOM is sufficiently acquired right after a fault using "*Q margin securement control*", so it can prepare for N-1-1 contingency event.
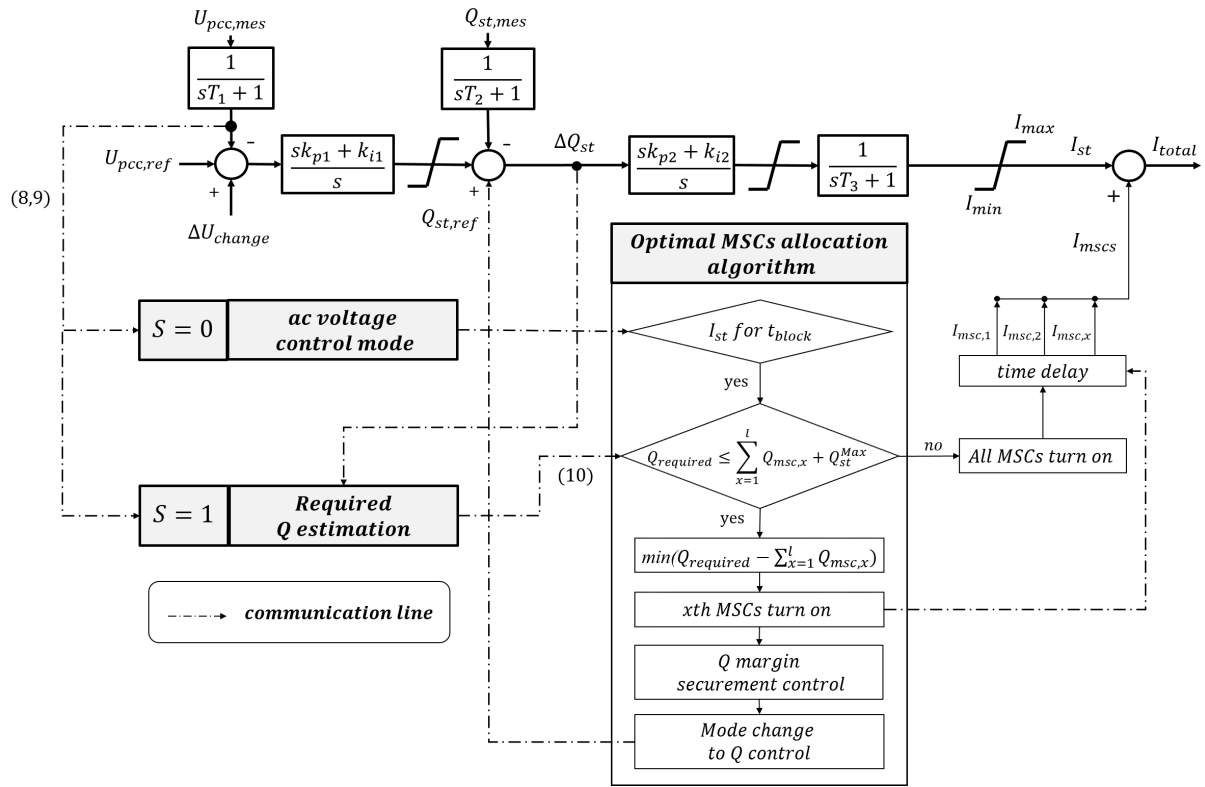
FIGURE 3. The proposed coordinated control block diagram of hybrid STATCOM.

- It reduces the costs of system losses per year due to correct and rapid voltage support.

C. HYBRID STATCOM MODEL DEVELOPMENT IN PSS®E

In order to apply the proposed control scheme into a real grid, the User Defined Model of Hybrid STATCOM is developed in the PSS®E environment. The PSS®E provides sufficient functionality to analyze a grid strength change, which is essential to this scheme. Since the generic model of Hybrid STATCOM has not yet been developed, the control block structures of STATCOM, MSCs, and coordinated controller are written by Fortran code, and the specific model parameters are presented in the simulation section.

With subsequent simulations with several grid condition, a correct dynamic response of developed reactive power compensator system was observed as shown in Fig.4 and 5, and several reactive power steps have been defined in order to test the voltage transient response. With the voltage reference signal, the STATCOM has no discontinuity in response from positive reactive power area to negative reactive power area, as shown Fig. 4, and for MSCs, as shown Fig. 5.

III. SIMULATION STUDY AND ANALYSIS

The objective of carrying out this simulation is to verify the performance of developed Hybrid STATCOM model, and to evaluate the performance of proposed control strategy. It was assumed that there was one STATCOM system in
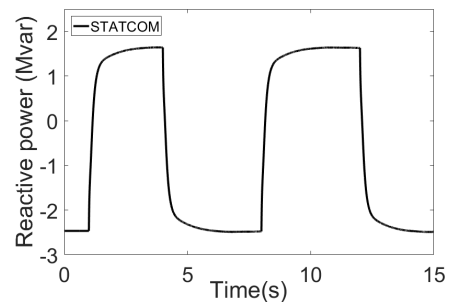

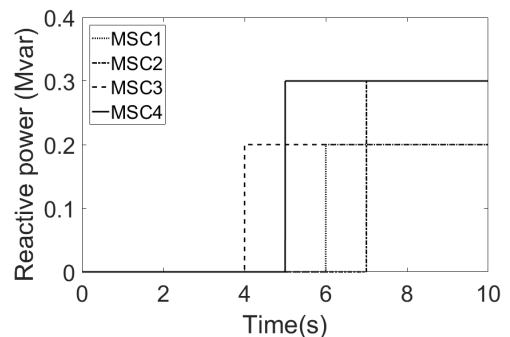**FIGURE 4.** Reactive power output characteristic of STATCOM in PSS ® E.

FIGURE 5. Reactive power output characteristic of MSCs in PSS ® E.

the Jeju island power system in Korea to prevent a voltage swing. Generally, multiple STATCOMs support the grid voltage based on their droop characteristics since reactive power

compensation with PI controller can cause circulating current in the grid. But, this island power system includes a single STATCOM so that ac voltage control based on PI controller was adopted.

There are three sets of data that are compared, as shown in Table 1. The *case 1* is to compare between only STATCOM and Hybrid STATCOM. The *case 2* and *3* are to compare different control strategies with a same capacity of Hybrid STATCOM. Three cases are all applied in Jeju island with peak load condition, and grid and control parameters are represented in Table 2 and 3, respectively.

TABLE 1. System specification for three cases.

	Control scheme	Capacity
Case 1	Only STATCOM	STATCOM #1
Case 2	Hybrid STATCOM with Conventional Scheme	STATCOM #1 MSC #1
Case 3	Hybrid STATCOM with Proposed Scheme	MSC #2 MSC #3 MSC #4

TABLE 2. Grid Parameters.

LCC HVDC #1, #2	200 MW	Hyb. STATCOM capacity	250 Mvar/ 50 Mvar
Wind Capacity	40 MW	MSC #1 capacity	20 Mvar
Jeju TP2	46 MW	MSC #2 capacity	45 Mvar
Jeju DP1	28 MW	MSC #3 capacity	70 Mvar
Jeju DP2	28 MW	MSC #4 capacity	65 Mvar
Namjeju TP3	65 MW	Hyb. STATCOM bus voltage	154 kV
Namjeju TP4	73 MW	Droop slope of MSCs	0.02
Total load	685.86 MW	Time delay of each MSCs	1 s
Total Generation	698.14 MW	Grid Frequency	60 Hz

According to the Table 2, the turn on time for MSCs is all applied at $t = 4s$, and each MSC has a mechanical time delay of 1s. The droop slope D_x is used as 0.02 in all cases for ease for calculation. Also, the parameters were evaluated with impedance stability analysis to prevent resonance between grid and controllers. Following the earlier approaches [25], [26], PWM switching delay was approximated by a first-order Padé approximation and the output terms as current of d-q frame were derived to configure a converter admittance transfer function. Then, the stability between the ac grid and converter was analyzed based on the initial operating point of STATCOM.

A. INDEX DEVELOPMENT FOR BASIC TRANSIENT STABILITY EVALUATION

In order to overview basic differences between three cases, two indexes of voltage dip time duration as S_τ, and maximum transient voltage dip as S_v are used, respectively. The S_τ and S_v are calculated by:

$$S_\tau = \tau_{dip} = \tau_2 - \tau_1 \qquad (12)$$

TABLE 3. STATCOM parameters.

k_{p1}	2	PLL gain	120
k_{p2}	2	PLL integral	1400
k_{i1}	150	q-axis current control gain	1.5
k_{i2}	200	q-axis current control time constant	0.05
T_1, T_2, T_3	0.02	V_{ref}	1.02

$$S_v = V_{dip} = V_{ref} - V_{min} \qquad (13)$$

where, τ_1 is the time at which the transient voltage dip begins, and τ_2 is the time which the transient voltage dip ends as shown in Fig. 6. Thus, it can be noted that if system cost and two indexes are small, the system will be cost-effective and perform well.
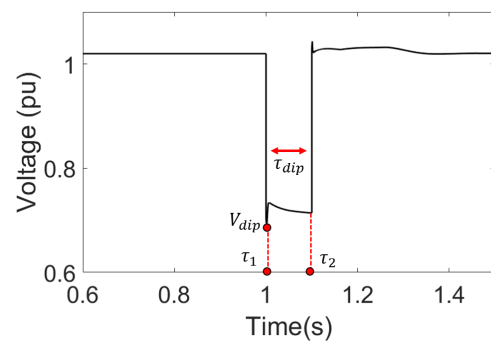

FIGURE 6. Transient stability index for S_τ and S_v.

The *case 1*, which has a 250Mvar STATCOM capacity, has a powerful strength during transient stability. As a result, the S_τ is the lowest among three cases. But, note that the price per kVar is about 5-6 times higher than MSC [27], the result shows that there is an explicit tradeoff between the cost and two indexes, as shown in Fig. 7.
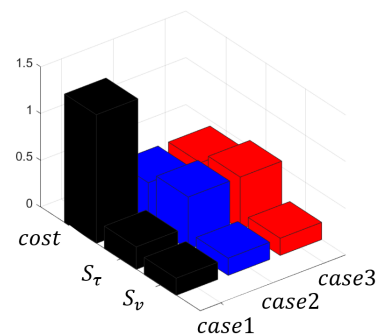

FIGURE 7. Cost and stability index result comparison between three simulation cases.

In conclusion, we intuitively know that the topology of Hybrid STATCOM can be a cost-effective measure for grid operators. In *cases 2* and *3*, as can be observed, no difference between two cases provides some information that the transient response derived by each control strategy is not much different. But, it makes sense that the *case 2* and *3* have a
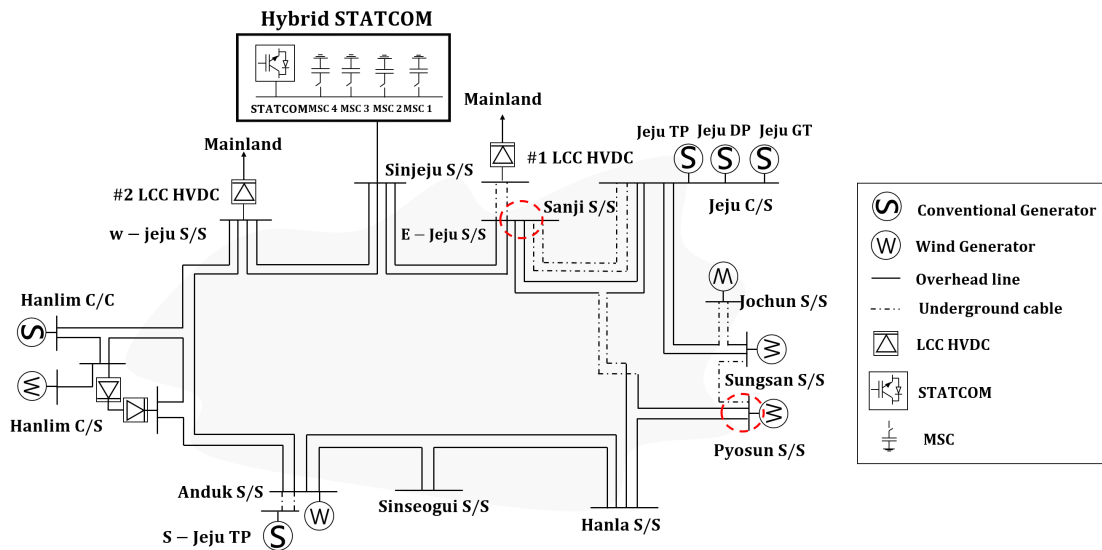
FIGURE 8. Hybrid STATCOM in Jeju island power system.

same STATCOM capacity as 50Mvar based on Table 1, and also have smaller capacity than *case 1*, that S_τ and S_v indexes are naturally higher than *case 1*, and that the installation cost is also low. The index shows an expected result that the MSCs have a mechanical time delay that could not contribute right after the fault.

B. MORE DETAILED COMPARISON BETWEEN CASE 2 AND 3

Two control algorithms are specifically compared in the short-term, and three scenarios as *light, severe, and N-1-1 contingency* are included, respectively. The *light contingency* shows a low voltage dip, and the fault point as "PYOSUN" bus is electrically far from the Hybrid STATCOM bus as shown in Fig.8. On the other hand, the *severe contingency* at "SANJI" shows a high voltage dip, and the fault occurred nearby Hybrid STATCOM bus. The contingency time line is all the same as follows:

1. Simulation Start time: 0 s
2. Apply 3-phase fault at "PYOSUN" or "SANJI": 1 s
3. Remove Fault and Trip lines: 1.1 s
4. Simulation End: 8 s

Only for the *case 3*, the $Q_{required}$ was updated online using OGSL; thus, the Fig. 9 shows the continuously updated $U_{PCC} - Q_{required}$ droop slope according to each load level using (8) and (10).

Note that the peak load condition has a high *OGSL* index, it requires larger reactive power amount to compensate the same ac voltage drop. On the other hand, the small reactive power was required in the light load condition. According to (10), by knowing $Q_{required}$ for *light* and *severe contingency* events, the $Q_{required}$ can be calculated, as shown in Table 4.
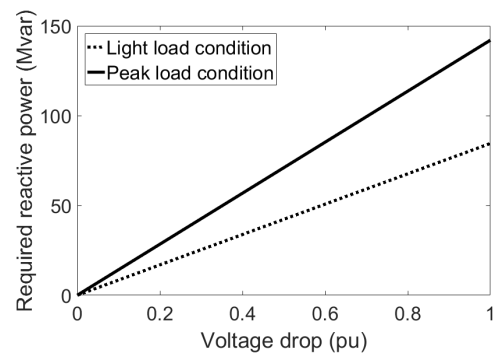

FIGURE 9. Required reactive power amount result depending upon grid topology.

TABLE 4. Required reactive power estimation result.

| Load condition	Scenario case	ΔV_{dip} (pu)	$Q_{required}$ (Mvar)
Peak Load	Light contingency	0.016	69.2
	Severe contingency	0.075	317

1) LIGHT CONTINGENCY

In the *light contingency* case, *case 1* was well prevents the voltage dip, as shown by black lines in Fig. 10-(b). As mentioned earlier, however, it is not an economic alternative for gird operators due to a high installation price. In *case 3*, four MSCs keep their capacity updated using (11) and the optimal MSCs are selected based on the $Q_{required}$ result, as shown in Table 5. The "MSC #3" as 68.97Mvar is selected for the optimal compensation amount. On the other hand, the conventional control scheme as *case 2* turns on the "MSC #1" and "MSC #2" step by step.

TABLE 5. Optimal allocation result of MSCs in the light contingency case.

	Capacity at *kth* time (Mvar)	Selected MSCs in case 3	Selected MSCs in case 2
MSC #1	18.5	X	O
MSC #2	43.5	X	O
MSC #3	68.5	O	X
MSC #4	63.5	X	X

(O : TURN ON / X : TURN OFF)
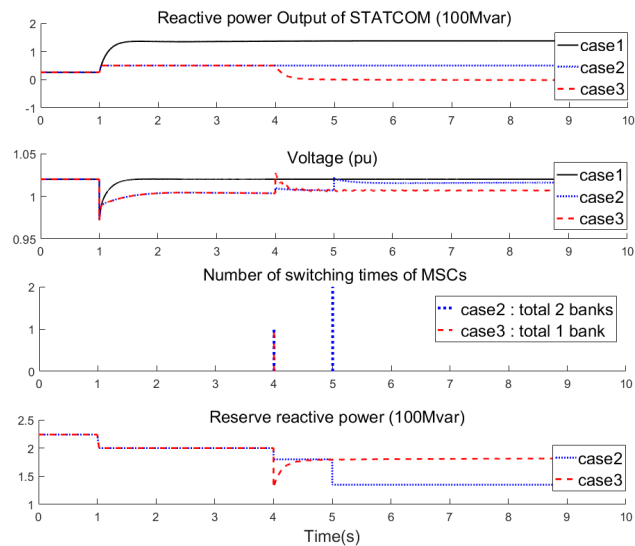
FIGURE 10. (a) Reactive power of STATCOM. (b) Grid voltage. (c) A number of switching times of MSCs. (d) Reserve reactive power.

First, the initial reactive power output of STATCOM for ac voltage control is 25Mvar; thus, all two case has a total 225Mvar (=250Mvar-25Mvar) of *Reserve reactive power*, as shown by overlapping blue and red lines in Fig.10-(d).

Given that the online $Q_{required}$ result was used in *case 3*, there are two major differences between *case 2* and *3*. In *case 2*, *Reserve reactive power* is consistently consumed after $t = 4s$, as shown by blue line in Fig.10-(a), although the remaining MSCs are turn on step by step, as shown in Fig.10-(c) with blue line. Thus, it is hard to acquire *Reserve reactive power* right after a fault. In *case 3*, however, using $Q_{required}$ makes possible to select the optimal capacity of MSCs; thus, grid operator knows that turning on the "MSC #3" will sustain allowable ac voltage range as 0.95pu to 1.05pu even though the STATCOM decreases its power. Hence, the STATCOM activates "Q margin securement control" at $t = 4s$, and sufficient *Reserve reactive power* can be acquired after 4s, as shown by red line in Fig. 10-(a). Due to the decreased reactive power of STATCOM in *case 3*, the total *Reserve reactive power* is higher than *case 2*, as shown in Fig.10-(d) with red line.

More detailed, the reason for activation of "Q margin securement control" is that the $Q_{required}$ amount was located between 0 and $\sum_{x=1}^{l} Q_{msc,x}(k)$. The grid operator knows that

the $Q_{required}$ from the grid can be compensated with a combination of MSCs; hence, the STATCOM can prepare other contingencies that increases grid reliability and flexibility. Second, in *case 2*, the Hybrid STATCOM should match the exact ac voltage reference at PCC bus; thus, two kinds of MSCs have to be turned on at $t = 4s$ and $5s$, respectively, as shown in Fig 10-(c) with blue line. The "MSC #2" was unnecessarily turned on although the grid voltage sustains its nominal stable voltage range as 0.95pu to 1.05pu. As a result, the number of switching times is larger than the *case 3*, as shown in Fig 10-(c) with blue line.

Results in Fig 10-(c) and (d) summarize the mean value with regard to the proposed strategy. The flexibility of *case 3* comes from the fact that $Q_{required}$ can be compensated by an optimal combination of MSCs. It stands out how many the *case 3* could reduce switching times of the MSCs, and how fast the sufficient *Reserve reactive power* amount could be secured. The *case 3* becomes more powerful reactive power resource when the continuous contingencies occur.

2) SEVERE CONTINGECN
Far more *severe contingency* in Jeju island power system is applied. Given that the contingency scale, STATCOM of three cases reaches it maximum capacity in transient state as shown in Fig. 11-(a). In the proposed strategy, the $Q_{required} = 317Mvar$ was updated in accordance with (10). But, it is higher than a sum of installed capacity of MSCs; therefore, all MSCs should be activated, as shown by red line in Fig.11-(c). The total number of switching times for MSCs is same between cases 2 and 3. Hence, by knowing the $Q_{required}$ result, the proposed scheme only has a one advantage that the grid voltage is more rapidly compensated than *case 2*, as illustrated in Fig.11-(b) with red line. In the *case 2*, the operators cannot know the degree of voltage change after a certain MSC input, therefore, the MSCs are turned on step by step to observe the grid voltage variation.

3) N-1-1 CONTINGECNY
To escalate the effectiveness of proposed strategy, *N-1-1 contingency* simulation was performed in this section. The first contingency is applied at $t = 1s$ in "SANJI" bus, and the second contingency occur at $t = 5s$ in "PYOSUN" bus. Through the optimal allocation algorithm in *case 3*, the "MSC #2", "MSC #3" and "MSC #4" are selected to compensate about 160Mvar during the first voltage dip as shown in Table 6 , and they are injected at $t = 4s$ at once, as shown in Fig.12-(c) with red line.

In the first voltage dip, STATCOM activates the "Q margin securement control" that reduces its reactive power output at $t = 4s$, since the $Q_{required}$ amount was located between 0 and $\sum_{x=1}^{l} Q_{msc,x}(k)$, as shown by red line in Fig 12-(a).

During the second voltage dip, the STATCOM generates reactive power again at $t = 5s$, and the remain "MSC #1" is turned on at $t = 6s$ in *case 3*. As we can be observed in Fig 12-(b), the *case 3* can prevent the second voltage dip at
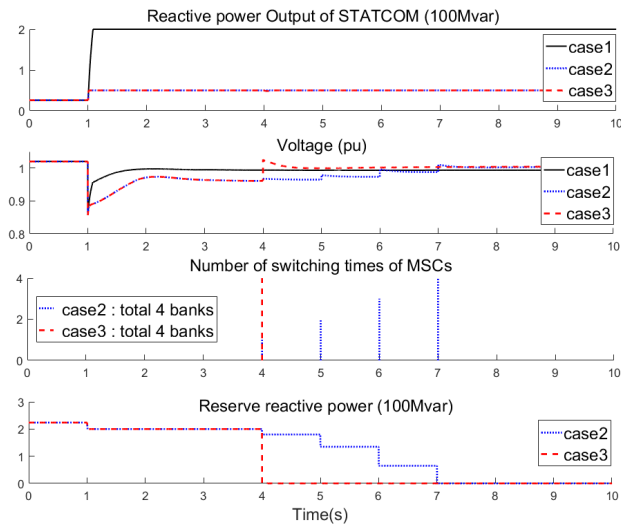
FIGURE 11. (a) Reactive power of STATCOM (b) Grid voltage. (c) A number of switching times of MSCs. (d) Reserve reactive power.
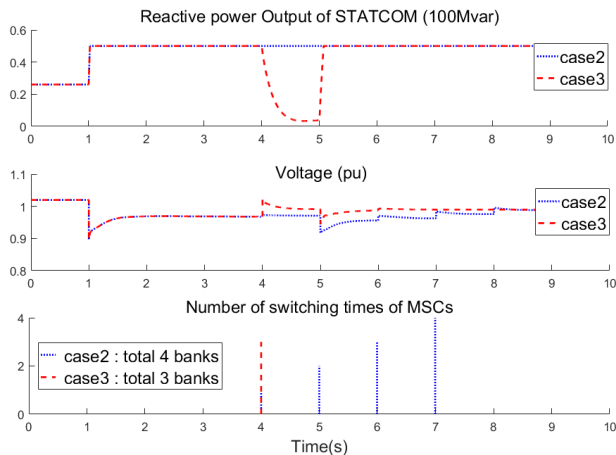

FIGURE 12. (a) Reactive power of STATCOM. (b) Grid voltage. (c) A number of switching times of MSCs.

TABLE 6. Optimal allocation result of MSCs in N-1-1 contingency in first voltage dip.

	Capacity at kth time (Mvar)	Selected MSCs in case 3	Selected MSCs in case 2
MSC #1	15.5	X	O
MSC #2	40.5	O	X
MSC #3	65.5	O	X
MSC #4	60.5	O	X

(O : TURN ON / X : TURN OFF)

$t = 5s$ effectively due to the large *Reserve reactive power* and the it shows more improved voltage recovery characteristics than *case 2*.

But, the total switching frequency of MSCs is the same for two cases in the last, as illustrated in the Fig 12-(c). In conclusion, frequent switching may increase the wear and tear of switchgear, and this would eventually affect operational costs due to the increased maintenance and reduce the lifetime of equipment, which is typically limited to 10,000-100,000 switching operation. Also, when a certain MSC is switched off, it is not possible to switch it on again immediately, unless the capacitor is discharged. The system, therefore, some waiting time is needed for a MV-unit MSC. This is the reason that the switching behavior should be clearly and economically. From this point of view, the proposed scheme is more effective than the conventional strategies, especially under N-1-1 contingency.

IV. CONCLUSION

This paper has analyzed a possible solution to operate Hybrid STATCOM system more flexibly. The proposed solution is based on the required reactive power estimation method and optimal allocation algorithm of MSCs, which are newly presented in this paper. With the proposed scheme, the Hybrid STATCOM acts more flexibly in the changing grid status. Hence, the analysis presented and the results obtained in this paper are a valuable and interesting reference that could be used by future Hybrid STATCOM operators since the grid would momentarily require different reactive power amounts.

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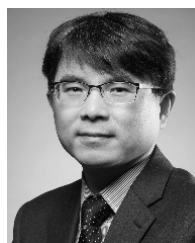
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