Security Constrained Intelligent Reconfiguration of MVDC Shipboard Power System

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Abstract—One of the distribution architectures proposed by Navy for their future shipboard power systems is Medium Voltage DC (MVDC) architecture. This system architecture is based on paralleling several voltage source converters (VSCs) to form Multi-Terminal MVDC. When fault occurs, protection systems isolate the faulty part, and VSC fault will lead to change in power flow and bus voltages. Remaining converters in the system after the fault may be damaged due to over-voltage. This can happen very quickly before the controllers reset power settings of VSCs to optimize the power flow and voltages. One way to solve this problem is to predetermine the power settings to meet the voltage constraints even with limited number of most common contingencies. Two types of VSCs in the grid including load and generator VSCs have been assumed in the system. In this paper, N-2 security constrained MVDC reconfiguration problem has been solved using genetic algorithms. Results of the proposed optimization problem show satisfactory results to control the power settings of MVDC notional shipboard power system test case.

Index Terms—Genetic algorithms, optimization, power converters, power system security.

I. INTRODUCTION

One of the distribution architectures that Navy has proposed for their future shipboard power systems is Medium Voltage DC (MVDC) with the goals of maximizing reliability, intensifying operational flexibility, minimizing size & weight, and decreasing the overall cost [1], [2].

The MVDC grid consists of parallel voltage source converters (VSCs) to create a Multi-Terminal system. Generally, all of these VSCs except one act as power dispatchers that can inject or draw power from the DC Grid. One of the VSC is DC voltage regulator or slack VSC that compensates for injected or drawn power to balance power within the DC grid. Slack VSC also regulate its reference bus voltage with feedback control [3], [4].

Fault can occur because of combat damage or equipment failure. After fault occurrence, protection system isolates VSC and power flow of DC power system will change. Voltage of buses in DC grid will increase due to loss of load VSC and will decrease due to loss of generator VSC. Restored converters in the system after the fault may be damaged due to over-voltage. This can happen very quickly before the controllers reset power settings of VSCs to optimize the power flow and voltages. Therefore, there is no time for the controllers to reset power settings of power dispatcher VSCs [4]–[6]. For this reason, power settings should be predetermined to meet the voltage constraints in any possible situations which are: 1) normal situation that all VSCs are working, 2) after the loss of one load or one generator VSC and 3) consecutive loss of two load or generator VSC. There are \( N - 1 + \binom{N-1}{2} \) number of possible contingencies for post fault DC power flow, where \( N \) is number of buses in the network. For all possible cases DC power flow problem needs to be solved concurrently in normal situation. DC power flow can be solved using Newton-Raphson method [7]. For simplicity, the assumption is that faulted VSC will not be the DC voltage regulator because its role can be transferred to other VSCs in the case of failure. This setting can be maintained by the embedded control scheme of each VSC.

The described problem can be formulated as an optimization problem which is a complex, large scale and multi-objective optimization problem. To deal with this hard-to-solve nonlinear optimization problem intelligent method such as Genetic Algorithm (GA) has great advantages. GA can deal with any nonlinear optimization problem with low computational cost. GA is a random local search technique based on the biological evolution mechanics and was designed to find a near optimal solution in a large and complex search space [8], [9].

This paper at first introduces (N-2) security constrained MVDC reconfiguration problem and formulates it into an optimization problem. The optimization problem is described as optimizing the reference power setting of VSCs in MVDC notional shipboard power system model. Then it briefly explains Genetic Algorithm (GA) and shipboard power system MVDC model. At the end, result of developed GA method for solving the optimization problem is presented. In previous research works in our group [10], [11], (N-1) contingencies have been solved for MVDC system, but this work determines the optimal reference power settings of the power dispatcher converters (load or generator VSC) ensuring that the DC voltage across these VSCs also remains within acceptable bonds in the normal system condition as well as under failure of one of the power dispatcher VSCs or under failure of a power dispatcher VSC that is followed by the loss of another power dispatcher VSC.

II. N-2 SECURITY CONSTRAINED MVDC RECONFIGURATION PROBLEM

The MVDC grid includes \( N \) number of VSCs at their DC terminals and this system is called a multi-terminal MVDC.
system. N-1 number of these VSCs are power dispatchers that can inject or draw power from the DC Grid. Nth VSC is DC voltage regulator or slack VSC that compensate injecting or drawing power to balance the overall DC grid load with generation and also regulating its reference bus voltage with feedback control. Fig. 1 illustrates MVDC grid including N number of VSCs in normal situation.

When one or multiple DC faults occurs in the MVDC grid because of equipment failure or battle damage, after fault isolation via the protection system, the total impact is on steady state voltages across power dispatcher VSCs.

For example. Fig. 2 illustrates MVDC grid including N voltage source converters after 2 faults occurred on a generator VSC and on a load VSC, respectively. After fault occurrence, protection system opens corresponding circuit breakers and isolates the faults.

Therefor the goal is to pre-determines the optimal reference power settings of the power dispatcher converters (load or generator VSC) ensuring that the DC voltage across these VSCs also remains within acceptable bonds in the normal system condition as well as under failure of one of the power dispatcher VSCs or under failure of a power dispatcher VSC that is followed by the loss of another power dispatcher VSC. The problem that was described can be formulated as an optimization problem with the objective to find the power settings of dispatcher VSCs. This optimization problem includes decision variables, objective function, equality constraints, and inequality constraints as described in following subsections.

A. Decision Variables

Number of decision variables in the optimization problem can be obtained as:

\[
\# \text{ of variables} = (N - 1) + (N - 1) + (N - 1)(N - 1) + \frac{(N - 1)2}{2} (N - 1)
\]

where:

- \(P_i\): Power setting of \(i\)th VSC for \(i = 1, 2, \ldots, N - 1\).
- \(V_i^0\): Voltage of bus \(i\) when all VSCs are working for \(i = 1, 2, \ldots, N - 1\).
- \(V_j^1\): Voltage of bus \(i\) when \(j\)th VSC is permanently lost for \(i, j = 1, 2, \ldots, N - 1\).
- \(V_{j,m}^2\): Voltage of bus \(i\) when \(j\)th and \(m\)th VSCs are permanently lost, respectively, for \(j \neq m\) and \(i, j, m = 1, 2, \ldots, N - 1\).

B. Objective Function

Proposed optimization problem has multi-objective function which is converted to weighted sum objective function and is described as follows:

\[
C = W_1 \sum_{j=0}^{N-1} \sum_{i=1}^{N-1} (V_i^j - V_{\text{slack}})^2 + W_2 \sum_{j} \sum_{m=1}^{N-1} (V_{j,m}^2 - V_{\text{slack}})^2 + W_3 \sum_{i=1}^{N-1} (P_{i} - P_{\text{min},i})(P_{i} - P_{\text{max},i}) + W_4 P_{\text{loss}}
\]

The objective function consists of four terms. First term minimizes the difference between reference voltage (1 pu) and bus voltages in both normal condition and in case of losing one dispatcher VSC (N-1 contingency). Second term minimizes the difference between reference voltage (1 pu) and bus voltages in N-2 contingency. The third term is to set power setting of dispatcher VSCs to have maximum deviation from their predefined minimum and maximum. Power settings of load VSC will be forced to same value through their inequality constraint, and the last one is to have the minimum network loss with power settings of VSC dispatchers, \(W_1\), \(W_2\), \(W_3\), and \(W_4\) are weighting factors.
C. Equality Constraints

The following N-1 sets of equations in (3) are power flow equations in normal situation when all VSCs are in line.

\[ P_i = \sum_{k=1}^{N-1} [V_i^0 y_{i,k} V_k^0 + V_i^0 y_{i,N} V_{\text{slack}}] \]  \hspace{1cm} (3)

where \( y_{i,k} \) is the admittance of the line between node \( i \) & \( k \) and \( i = 1, 2, \ldots, N - 1 \).

The following \((N-1)(N-1)\) sets of equations in (4) are power flow equations when \( j \)-th VSC is permanently lost and its injected power is set to zero (left hand side of the equation).

\[ P_i = \sum_{k=1}^{N-1} [V_i^j y_{i,k} V_k^j + V_i^j y_{i,N} V_{\text{slack}}] \]  \hspace{1cm} (4)

where \( i, j = 1, 2, \ldots, N - 1 \) and if \( i = j \) then \( P_i = 0 \).

The following \((N-1)(N-1)\) sets of equations in (5) are power flow equations when \( j \)-th and \( m \)-th VSCs are permanently lost respectively and their injected power are set to zero (left hand side of the equation).

\[ P_i = \sum_{k=1}^{N-1} [V_i^{j,m} y_{i,k} V_k^{j,m} + V_i^{j,m} y_{i,N} V_{\text{slack}}] \]  \hspace{1cm} (5)

where \( i, j, m = 1, 2, \ldots, N - 1 \), \( j \neq m \) and if \( i = m \) or \( j = m \) then \( P_i = 0 \).

Total power losses of the network in normal condition can be computed using (6):

\[ P_{\text{loss}} = \sum_{\text{all branches}} |y_{i,k}|(V_i^0 - V_k^0)^2 \]  \hspace{1cm} (6)

Number of equality constraints in proposed optimization problem can be obtained by the following equation:

\[ \# \text{ of equality constraints} = \frac{(N-1)(N-1) + (N-1)(N-1) + (N-1)(N-1) + 1}{2} 
\frac{N^2 - N + (N-1)(N-2)}{2}(N-1) \]  \hspace{1cm} (7)

D. Inequality Constraints

Bus DC voltages in all three conditions should be maintained in their secure limits. The following \( N - 1 \) sets of inequalities are bus DC voltages in their secure limit when all VSCs are in line.

\[ V_{\text{min},i} < V_i^0 < V_{\text{max},i} \]  \hspace{1cm} (8)

where \( i = 1, 2, \ldots, N - 1 \).

The following \((N-1)(N-1)\) sets of inequalities are bus DC voltages in their secure limit when \( j \)-th VSC is permanently lost.

\[ V_{\text{min},i} < V_i^j < V_{\text{max},i} \]  \hspace{1cm} (9)

where \( i, j = 1, 2, \ldots, N - 1 \).

The following \((N-1)(N-1)\) sets of inequalities are bus DC voltages in their secure limit when \( j \)-th and \( m \)-th VSCs are permanently lost respectively

\[ V_{\text{min},i} < V_i^{j,m} < V_{\text{max},i} \]  \hspace{1cm} (10)

where \( i, j, m = 1, 2, \ldots, N - 1 \) and \( j \neq m \).

Power settings of all VSCs should be in their desire limit. For example for load VSC, the desire limit can be selected too narrow to prevent load shedding after optimization.

\[ P_{\text{min},i} < P_i < P_{\text{max},i} \]  \hspace{1cm} (11)

For load VSC we have \( P_i < 0 \) then \( P_{\text{min},i} = P_{\text{max},i} = P_{\text{initial load}} \).

Number of inequality constraints in proposed optimization problem can be obtained by

\[ \# \text{ of inequality constraints} = \frac{V_i^0}{(N-1) + (N-1)(N-1) + \frac{V_i^j}{(N-1) + (N-1)}} \]

\[ \frac{V_i^{j,m}}{(N-1) + (N-1)} + \frac{P_i}{2} \]

\[ \frac{N^2 - N + (N-1)(N-2)}{2}(N-1) \]  \hspace{1cm} (12)

The equation to balance the overall DC grid load with generation and power losses is expressed in (13).

\[ P_{\text{slack}} = -(P_1 + P_2 + \cdots + P_{N-1}) + P_{\text{loss}} \]  \hspace{1cm} (13)

where \( P_{\text{slack}} \) is Power setting of \( N \)-th VSC (DC Voltage regulator or slack VSC).

It is worth to mention that the optimization problem is a complex problem. For instance for a 7 bus system, typical ship board power system, the optimization problem has 138 decision variables, 132 equalities and 138 inequalities with a nonlinear weighted sum objective function.

III. GENETIC ALGORITHM

GA was invented by John Holland in the early 1970s and now is applied on a wide range of problems of planning, scheduling, and optimization [5-6]. It is a random local search technique based on the biological evolution mechanism and was designed to find a near optimal solution in a large and complex search space. One of its great characteristic is to overcome getting trapped at a local optimum which is the main deficiency of a generic local search algorithm. The general structure of GA pseudo code is as follows:

Algorithm 1 GA pseudo code

\begin{itemize}
  \item Initialize Population (solution sets)
  \item \textbf{while} (termination rule! = true) do
    \item Evaluate Fitness (objective function)
    \item Select Population (GA operator)
    \item Crossover Population (GA operator)
    \item Mutate Population (GA operator)
  \item \textbf{end while}
\end{itemize}
Initialization, crossover and mutation are stochastic procedures; therefore, GA is stochastic process. Because of this characteristic there is always chance to stuck in local optimum or not converge, especially in non-linear optimization problems. However, in this work, every test case has been run several times to minimize this chance and all runs showed consistent results. In test cases, size of population and generation have been taken as 100.

IV. MVDC Model For Shipboard Power System

The MVDC shipboard power system used in this study is based on MVDC zonal based model developed by Center of Advanced Power Systems (CAPS) at Florida State University. The recommended MVDC network is comprising of two main generation gas turbines units with 36 MW output power (MTG1 and MTG2) and two auxiliary gas turbines units with 4 MW output power (ATG1 and ATG2). Loads for this Medium Voltage DC network are two 36.5 MW propulsion motors (PM1 and PM2), one 3 MW radar, pulse load weapon, and operational systems, etc. Voltage of the main DC bus is \( \pm 5000 \text{ V} \) which provides power for five load zones. Each zone is fed by \( \pm 800 \text{ V} \) with a DC-DC converter (PCM1). The power for AC loads is provided by 450 V through the DC-AC inverter (PCM2). The HP sensor is high power radar and energy storage unit consist of fuel cells and capacitors. The recommended model is illustrated in Fig. 3.

V. Case Study and Simulation Results

Shipboard power system MVDC model presented in Fig. 3 has been modified as a 7-bus MVDC grid in Fig. 4. The proposed method of (N-2) security contrived optimal power control setting has been tested on this simplified model. VSC7 is assigned to be voltage regulator and therefore bus number 7 is the slack bus. VSC2, VSC3, VSC5 are connected to the main and auxiliary generators on the AC side and are acting as rectifiers. Loads are connected to VSC1, VSC4, VSC6 which are acting as inverters. Table I shows load value assumptions in per unit1.

Table II shows DC resistances assumptions of all the DC lines in Fig. 4. The DC line resistances are typically small values as the cable length between the converters is few meters and the value has been calculated for the system of 5000 V voltage rating, and considering the DC resistance at 25° as 0.0361Ω per 1000 m.

After running the developed script base on evolutionary computational algorithm optimal converter power settings are presented in Table III. Table IV summarizes the simulation results of DC bus voltages in all contingencies. In this study, average of several GA runs has been taken as the reported result. It can be observed that the adjusted power settings satisfy the system operating constraints not only under the normal condition, but also under outage of the one or two power dispatcher VSCs. To compare the proposed method with the base case (optimal power flow) and (N-1) contingencies case, these methods were solved for the same system. It turned out for this small test case voltages are within the limit for both the pre-fault and post-fault contingencies but as we expected, voltage profile is closer to nominal voltage (1 pu) in the proposed method and basically it is flatter. To show the flatness of the voltage profile and evaluate the performance of the proposed method a simple metric (error) for each bus under total number of contingencies, which is 22 in our case, is defined as below:

\[
Er_i = \frac{1}{N_{cont}} \sum_{k=1}^{N_{cont}} (V_i^k - V_{slack})^2
\]

where \( N_{cont} = 1 + (N - 1) + \left(\begin{array}{2}N - 1 \\ 2 \end{array}\right) \) is the total number of contingencies and \( V_i^k \) is the voltage of bus \( i \) under contingency \( k \). Fig. 5 illustrates the defined metric for three cases.

Figs. 6 and 7 depict bus voltage of all VSCs in 22 different contingencies in order to improve the readability of the Table IV. As it can be observed, all the voltages are within
TABLE IV

**OPTIMAL CONVERTER POWER SETTINGS**

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<th>Contingency #</th>
<th>Lost VSC</th>
<th>V1 (pu)</th>
<th>V2 (pu)</th>
<th>V3 (pu)</th>
<th>V4 (pu)</th>
<th>V5 (pu)</th>
<th>V6 (pu)</th>
<th>V7 (pu)</th>
<th>Floss (pu)</th>
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VI. SUMMARY

We studied the formulation and solution method of N-2 security constrained reconfiguration of MVDC shipboard power system. The problem was formulated as an optimization problem and GA evolutionary computational algorithm was proposed. Seven-bus modified representation of the multi-zonal notional MVDC architecture was used as a test case. The simulation results indicate that voltages can be successfully controlled within normal bounds in the normal condition of the grid and under outage of one or two power dispatcher VSCs.
Fig. 6. BUS voltages of VSC\textsubscript{1}, VSC\textsubscript{2} and VSC\textsubscript{3} in per unit for 22 different contingencies.

Fig. 7. BUS voltages of VSC\textsubscript{4}, VSC\textsubscript{5} and VSC\textsubscript{6} in per unit for 22 different contingencies.

 REFERENCES


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