Impact of Placement of Inductive Fault Current Limiters on Synchronized Operations of Generators

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Abstract—Judicious placement of inductive fault current limiters (IFCLs) in isolated power systems can increase the robustness of generator synchronization during and after short-circuit faults, while also improving continuity of power to the system loads. Our work defines optimal placements of IFCLs so as to protect the synchronization of multiple generators, and it defines the proper trip settings for the IFCLs so that they coordinate well with each other, and with the system’s circuit breakers. Our work considers both radial and ring bus structures, but not mesh structures. The IFCL placement technique is demonstrated in a power network containing four buses in a ring arrangement. The system receives power from two main turbo-generators (36 MW each) and two auxiliary turbo-generators (4 MW each). In this system, the optimal locations for the IFCLs were found to be near the bus ties of the two larger generators. Further, the placement strategy for locating IFCLs in a power system with ring structure is developed. For this arrangement, fault currents were limited for all fault conditions while assuring maximum availability of power to the loads. Coordination between the IFCLs and the system circuit breakers is analyzed for IFCLs in these locations, and verified by simulation results.

Index Terms—fault current limiter, inductive, placement, synchronization

I. INTRODUCTION

As generation is added to increase the capacity of a power system, larger available fault currents may cause the existing circuit breakers to become under-rated. Otherwise, excessive dynamic stress during severe faults may result in failure of circuit breakers to open. Larger fault currents may also adversely influence synchronization of the generators, shorten the life of electric machines, or even cause complete failure of the equipment. Fault current limiters (FCLs) can prevent all of these disruptive events by limiting currents during faults and by increasing the robustness of generator synchronization. The choice of where in a system to place current limiting devices to best maintain synchronization among generators has become a significant issue, for which we propose a solution.

References [1] and [2] describe how genetic algorithms can be used to find the optimal placements of the minimum number of FCLs to meet maximum fault current objectives. After specifying a maximum desired fault current, combinations of FCLs at different locations are compared to find the optimal placements. The impedances and number of devices are regarded as a weight to optimize grouping. With this method, the minimum number and minimum impedances of FCLs were applied to satisfy the limitation of fault currents. For the case of an original system with newly-added distributed generation (DG), references [3] and [4] analyzed the influence on the relay scheme of FCLs, which are installed in several possible locations in the original system. The study proved that when the FCL is located near the DG, it limits the fault current while minimizing the problems associated with the protection scheme. These papers reveal the best placements in the utility grids. In [5], the FCL’s performance on limiting the extent of voltage sags and interruptions in shipboard power systems is revealed. The influence of FCLs on the transient stability of a power system is analyzed in [6] [7].

In this paper, we analyze the influence of IFCLs on generator synchronization. Based on the analyses, the optimal placements of IFCLs have been found to be near the bus ties of the two larger generators in the studied system, which is composed of two main turbo-generators (MTGs) of 36 MW and two auxiliary turbo-generators (ATGs) of 4 MW configured in a four bus arrangement in a ring configuration. The placement strategy for a power system having generators in a ring arrangement is as follows:

1. Place an IFCL at each MTG terminal to protect it from faults in its output cable, or in any bus connected to that cable.
2. Place one IFCL nearest to the MTG in any cable connecting an MTG bus with an ATG bus.
3. Place an IFCL at each end of any cable connecting the buses of any two main generators.

Such a configuration may be used in systems requiring high levels of fault-tolerance, such as in ships or in industrial plants running critical processes and having local backup power generating capacity. Especially in shipboard systems, distribution lines are short and hence of quite low impedance. The situation can easily lead to loss of synchronization among the generators during faults. With the placement of IFCLs as described here, fault currents can be limited under a user-defined value and also generator swing oscillations are limited and the system robustness is enhanced. Some key

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considerations in applying IFCLs to a power system, such as trigger level at which to activate an IFCL, how to coordinate between IFCLs and circuit breakers, are discussed and verified by simulation results.

II. SYNCHRONIZED OPERATIONS OF GENERATORS AND SYSTEM STRUCTURE

Generators must remain synchronized to keep them in generator-mode and to avoid large inrush of fault currents. Power distribution structures for systems of the types of installations considered here are of two main kinds: radial structure and ring structure, as shown in Fig.1. In these diagrams, the black blocks are circuit breakers and the round points are potential locations for IFCLs. The IFCL locations can be categorized as: (a) between generators and buses (to limit fault currents from generators); (b) between the buses (to limit power flow through the connecting cables); (c) at the load side of the buses (to limit the fault currents to load centers).

A. Radial structure

The radial structures are widely used in power systems [8], as shown in Fig.1 (a). Each generator mainly feeds the loads on its own bus but power can be shared among the buses via inter-bus cables.

B. Ring structure

The ring structure of a power system is shown in Fig.1 (b). In this structure, the cables form a loop among the buses and offer a more reliable supply to the loads than radial structure. If a fault occurs in any one cable, the faulty cable can be cut off by circuit breakers and the power can still flow through the other cables. In this way, load centers will not be affected and the power sharing among the generators is maintained the same as before a fault. The ring structure is often applied to electric-ship power systems because it is very robust. Also, many industrial power systems incorporate loop structures for similar reliability considerations.

C. Synchronized operations of generators

The impact of one IFCL on synchronized operation of two generators during fault conditions is analyzed, as shown in Fig. 2 where a fault short-circuits the load (not shown) to ground. \( V_1 \) and \( V_2 \) are similar ideal voltage sources. \( X_{FL} \) is the subtransient impedance of the sources. \( X_{FCL} \) is the impedance of IFCL. There is no IFCL installed in Fig. 2(a). During a fault, the system without IFCL is divided into two separate loops. There is no path for power exchange between the two power sources. By applying IFCLs, the generators become coupled through the common paths as shown in Fig. 2(b). The power can flow between the two generators via the new loop created by the impedance of IFCLs. The two generating sets are dragged by each other and kept in synchronism during the fault and after the fault is cleared. Based on this principle, the optimal placement of IFCLs for a network with four buses in ring structure is revealed in Section III.

III. OPTIMAL LOCATIONS OF INDUCTIVE FCLS

The optimal locations of IFCLs are investigated in a power network containing four buses in a ring arrangement. For the proposed placements of IFCLs, the system performances are presented with different fault locations in the system to limit the fault currents and protect synchronized operation of generators. The trigger level of inter-bus IFCLs is limited by the capacity of power network. Coordination between the IFCLs and circuit breakers is analyzed.

A. Power network with four buses in ring structure

The power network with four buses in ring structure, as shown in Fig. 3, is widely used in electric-ship power system. The system receives power from two main turbo-generators (MTG, 36 MW each) and two auxiliary turbo-generators (ATG, 4 MW each). The power flow through the cables, which connects the four buses, can be shared between the load centers.

B. Optimal locations of inductive FCLS

IFCLs in power systems must be able to limit fault currents regardless of where in the system the fault occurs. Due to cost considerations, the number of FCL devices should also be minimized. The possible placements of IFCLs are shown as round points in Fig. 3.

When the generators have the same or similar subtransient impedance in p.u., the fault current that can be supplied by the ATG is only 11.1 % (4 MW / 36 MW) that of the MTG. So, IFCLs are only installed between the MTGs and their bus feeders, as #1 and #6 in Fig. 3, and not installed at the ATGs.

The IFCLs (# 2 ~ # 5) are installed near the buses of MTGs, to limit fault currents through the cables. In this way, when a fault occurs in the middle of one cable, only one ATG, instead of one MTG, is isolated from the other generators during the transient (less than 0.1 s) that takes place between when the fault occurs and when the fault is cleared by the circuit breakers. In this case, two MTGs and the other ATG can remain synchronized during and after faults. With fast reclosing, the fourth generator can be returned to synchronization. The system oscillation is limited as far as possible.

C. Settings of IFCLs

When a fault occurs at the bus connected to MTG1 in Fig. 3, the fault currents through the cables should be equal or less than the fault current produced by 50 % of the capacity of the other system (36 MW + 2*4 MW = 44 MW) which follows Eq. (1), and the equivalent short-circuit impedance in p.u., \( X_{FL,Lumped} \). It is assumed that the IFCLs must be able to “see” faults at any places. Therefore, the trigger level of IFCLs should be less than the fault current produced by an equivalent
22 MW source, which equals $\sqrt{3} \times V \times X_{\text{d, lmped}}$, to guarantee the fault can be “seen” by the IFCL devices. $V$ is rated line-to-line voltage in electric power system. For example, there are two paths for fault currents to flow to the faulty bus, as shown in Fig. 4. If the impedances of the two cables are exactly the same, the fault current will be 50% of the fault current caused by the lumped power source (44 MW). If IFCLs limit fault currents under this ideally symmetrical structure, IFCLs can also “see” the faults of asymmetrical structures. So, the trigger level should be lower than this percentage to make sure IFCLs are triggered properly. For example, if fault happens on bus 4, the “faulty bus” in Fig. 4 is bus 4. The lumped power source with its equivalent impedance, in Fig. 4, refers to the dotted frame in Fig. 3. The $X_{\text{Cable 1}}$ and $X_{\text{Cable 2}}$, as shown in Fig. 4, refer to the cables between bus 4 and bus 3, bus 4 and bus 2 in Fig. 3 in this case. For different fault locations, the symbols in Fig. 4 represent different parts in Fig. 3.

On the other hand, the trigger levels of IFCLs at the side of MTGs, $I_{\text{MTG}}$, should be equal to or greater than the trigger level of the inter-bus IFCLs, $I_C$, to avoid disarray. For instance, if a fault occurs on the cable between MTG1 and ATG1, indicated by point A in Fig. 3, the IFCL of #2 should be triggered, not #1. The trigger levels of IFCLs should follow the limitations defined by Eq. (1), where $I_i$ is the fault current from the generator connected at bus $i$, and $k$ is the number of the faulty bus.

$$
\begin{align*}
I_{\text{MTG}} & \geq I_C \\
I_C & < \min \left( \frac{\sum_{i \in \text{faulty \ bus}} I_i}{2} \right)
\end{align*}
$$

Once triggered, the IFCLs stays at high-impedance status for 5 cycles (83.3 ms, 60 Hz), and then recovers to low-impedance status before the reclosing of the related circuit breakers. The sequence diagram is presented as Fig. 5. Some modern superconducting IFCLs can return to low impedance in 20 ~ 30 cycles (10 ms ~ 500 ms, 60 Hz), or even faster. For example, the "Cryo-Pinch" superconducting FCL is one kind of IFCLs which is based on the movement of the rotor with high reluctance sector produced by superconducting bias coil [9] [10]. This Cryo-Pinch with AC excitation responds three times faster than DC excited superconducting limiters and the reset time is dramatically faster, only 10ms, in contrast to DC excited devices which have reset times of 90s [9] [10].

D. Settings of circuit breakers

With the development of circuit breakers technology, the 2-cycle breakers are now commonly applied in electric power systems, although the 8-cycle, 5-cycle and 3-cycle breakers are still in use for utilities [11] ~ [13]. The new standard for reclosing allows one “O + 15 s + CO + 3 min + CO” or “O + 0.3 s + CO + 3 min + CO” for breakers intended for rapid reclosing [14] [15]. In this study, the breakers are set up to open in 5 cycles, followed by the reclosing time of 0.5 s, as shown in Fig. 5.

E. Analyses for various fault locations

When there is no IFCL installed in the network, the turbo-generators may lose synchronism during fault conditions, and their shaft speeds will increase according to the fuel flow of turbines and their power output.

When IFCLs are installed at the locations shown in Fig. 3, the conditions of faults on buses and cables are analyzed. The generator synchronization statuses are compared with and without IFCLs at the proposed optimal locations. The comparisons are classified according to three major conditions: fault at the bus connected to MTG2, fault at the bus connected to ATG1, and fault at the middle of the inter-bus cable:

- **Faults at the bus connected to MTG2:**
  
  When a fault occurs on bus 4, according to the setting of IFCLs mentioned in part III-C, IFCLs of #4 and #5 are triggered, while IFCLs of #1, #2 and #3 remain non-triggered. The IFCL of #6 is triggered to protect MTG2. During and after faults, MTG1, ATG1 and ATG2 remain synchronized. The load center at bus 4 temporarily loses the supply. After the reclosing of the breakers the supply to bus 4 recovers.

- **Faults at the bus connected to ATG1:**
  
  When a fault occurs on bus 2, IFCLs of #2 and #4 are triggered, while other IFCLs remain non-triggered. During and after faults, MTG1, MTG2 and ATG2 remain synchronized. The load center at bus 2 temporarily loses its power supply, but recovers after the reclosing of the breakers.

- **Faults at inter-bus cable:**
  
  When a fault occurs at point A in Fig. 3, IFCLs of #2 and #4 are triggered. During and after faults, MTG1, MTG2 and ATG2 remain synchronized. The load center at bus 2 loses power supply just during the period between when the fault occurs and when IFCL of #4 returns to the low-impedance status. After the breaker between point A and bus 2 opens, the supply on bus 2 recovers. The IFCL of #4 recovers to the low-impedance status and afterwards the operation of the system becomes stable.

The operating conditions of the network during various faults are summarized in Table 1. Based on the analysis above, the following placement strategy is developed for locating IFCLs in a power system with...
IV. SIMULATION RESULTS

In order to verify the efficacy of the proposed placement of IFCLs, a testbench with four turbo-generators in a ring-bus structure was implemented in VTB2009, which is the latest version of Virtual Test Bed [16]. The IFCL is modeled as a variable-inductance device that is controlled by a trigger port, with user-defined minimum inductance and maximum inductance. The turbo-generator model is based on the heavy-duty turbine model [17] and the full-order synchronous generator model [18]. These models are suitable for the analysis of dynamic power system studies. The parameters of the testbench are presented in Table 2. The default parameters of IFCLs are based on the "Cryo-Pinch" superconducting FCLs [9][10].

Fig. 6 shows the simulation environment and one turbine-generator set in detail. The synchronization controller [19][20] and the excitation system [21] adjust the shaft speed of the turbine and the magnitude of the excited voltage in order to synchronize the turbine-generator set prior to closing it into the network. The load centers are modeled as lumped R-L networks.

In the simulations, the rated current of the MTG is 5 kA, while the rated current of the ATG is 0.56 kA. According to Eq. (1), the upper bound of trip settings is 18.8 kA. So, the trigger level of IFCLs (#1, #6) is 17 kA, while the trigger level of IFCLs (#2 ~ #5) is 8.5 kA. The trigger logic measures the absolute value of instantaneous currents.

During normal operation, the four load centers are served by the four turbo-generators. The generating power ratio of the network with four buses in ring structure is greatly enhanced, with only six IFCLs installed at the proposed locations.

The influence of IFCLs on various fault locations has been analyzed. Based on the analysis of the relationship between frequencies when IFCLs are triggered, there is less power flows among generators and smaller system oscillations. Larger frequency differences are found if the IFCLs are not triggered. Since there are smaller differences among the generators, limit the power flow in the power system, and shorten the period of oscillation. The transient stability of the network with four buses in ring structure is greatly enhanced, with only six IFCLs installed at the proposed locations.

V. CONCLUSION

The influence of IFCLs on various fault locations has been analyzed. Based on the analysis of the relationship between
generator synchronization and system structure, the optimal placements of IFCLs are found to be near the bus ties of the two larger generators (MTGs) in a network composed of two MTGs and two ATGs in a ring structure. Further, the placement strategy is developed for locating IFCLs in a power system with ring structure. The simulation results verify that the proposed placement can effectively protect generator synchronization and enhance the transient stability of the network during faults, while also improving continuity of power to the system loads.

VI. REFERENCES


Fig. 1. Two kinds of basic power system structures: (a) Radial structure (b) Ring structure

Fig. 2. Comparison of generator synchronization, with and without IFCLs, when load circuit becomes short circuited.
Fig. 3. Power network with 4 buses in ring structure (two MTGs of 36 MW, two ATGs of 4 MW)

Fig. 4. Diagram of fault current flows in the network when a fault occurs at MTG2

Fig. 5. Sequence diagram of the trigger signal for IFCLs and open status of circuit breakers (fault occurs at t = 0 ms)
Fig. 6. Overview of the ring structure network and one of the power generating sets

(a) Overview of the network with a ring-bus structure in VTB2009

(b) Details of one MTG set
Fig. 7. Comparisons between fault currents flowing through the MTG and the inter-bus cable, with and without IFCLs.
(a) Frequencies when a fault occurs on the bus of MTG2

(b) Frequencies when a fault occurs on the bus of ATG1
Fig. 8. Comparison of frequencies during faults (a: fault on MTG2; b: fault on ATG1; c: fault on the inter-bus cable)

(c) Frequencies when a fault occurs on the inter-bus cable

Fig. 9. Fault currents through IFCL of #4 during fault on inter-bus cable (point A in Fig. 3)
(a) Real power outputs of MTG1

(b) Real power outputs of MTG2
Fig. 10. Comparison of real power outputs during faults on the bus of ATG1
### TABLE 1
**RUNNING STATUS DURING VARIOUS FAULTS**

<table>
<thead>
<tr>
<th>Fault Location</th>
<th>Fault on Bus_4</th>
<th>Fault on Bus_2</th>
<th>Fault on Cable (Point A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFCLs Triggered</td>
<td>#4, #5, #6</td>
<td>#2, #4</td>
<td>#2, #4</td>
</tr>
<tr>
<td>Generators Remaining Synchronized</td>
<td>MTG1, ATG1 and ATG2</td>
<td>MTG1, MTG2 and ATG2</td>
<td>MTG1, MTG2 and ATG2</td>
</tr>
<tr>
<td>Loads Centers Remaining Energized during Faults</td>
<td>BUS 1, BUS 2 and BUS 3</td>
<td>BUS 1, BUS 3 and BUS 4</td>
<td>BUS 1, BUS 3 and BUS 4</td>
</tr>
</tbody>
</table>

### TABLE 2
**PARAMETERS OF TESTBENCH FOR PROPOSED PLACEMENT OF IFCLS**

<table>
<thead>
<tr>
<th>Turbo-Generator</th>
<th>Rated Power</th>
<th>Rated Voltage</th>
<th>Power factor</th>
<th>Total inertia</th>
<th>Droop setting</th>
<th>( X_d )</th>
<th>( X_q )</th>
<th>( T_{d0} )</th>
<th>( T_{q0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTG1 CTG2 CTG3</td>
<td>36 MW (MTG)</td>
<td>4.16 kV</td>
<td>0.95 (lagged)</td>
<td>2.5 s</td>
<td>4 %</td>
<td>1.81 p.u.</td>
<td>1.76 p.u.</td>
<td>8.0 s</td>
<td>1.0 s</td>
</tr>
<tr>
<td></td>
<td>4 MW (ATG)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.3 p.u.</td>
<td>0.65 p.u.</td>
<td>0.03 s</td>
<td>0.07 s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IFCL</th>
<th>Increase time</th>
<th>Fall time</th>
<th>Maximum inductance</th>
<th>Minimum inductance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 ms</td>
<td>400 ms</td>
<td>10 mH</td>
<td>0.1 mH</td>
</tr>
</tbody>
</table>

### TABLE 3
**IMPROVEMENT OF SYNCHRONIZED OPERATION OF GENERATORS**

<table>
<thead>
<tr>
<th>Fault Locations</th>
<th>MTG2</th>
<th>ATG1</th>
<th>Inter-Rus Cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Includes IFCL?</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Maximum Frequency Bias (Hz)</td>
<td>0.18</td>
<td>0.25</td>
<td>0.19</td>
</tr>
<tr>
<td>Maximum Difference between Frequencies (Hz)</td>
<td>0.067</td>
<td>0.019</td>
<td>0.055</td>
</tr>
<tr>
<td>Duration of Oscillation (s)</td>
<td>5.5</td>
<td>4.5</td>
<td>5</td>
</tr>
</tbody>
</table>