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Fast Tuning Procedures for Emergency Controls Using Eigenvalue Computations

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ABSTRACT

In this paper, we propose a novel method for tuning the amount of generation tripping that would be used in conjunction with remedial action schemes (RAS) or special protection schemes. The method is motivated by the concept of unstable limit cycles and it utilizes fast eigenvalue computations. Unstable limit cycles play a crucial role in determining the transient stability margins of the power systems with weak interarea oscillatory modes. The western American power system WECC is an example where the transient stability is closely related to the existence of unstable limit cycles under certain operating conditions. For these systems, fast computational procedures based on estimation of the damping of the interarea modes, can be used for assessing the RAS generation tripping amounts. Eigenvalue based rules are presented in the paper and the results are illustrated on simulations of the phenomena in the standard Kundur two area test system which exhibits an interarea oscillatory mode.

1. INTRODUCTION

Dynamic security characterizes the ability of a power system to survive a set of credible contingencies with certain safety margin so that the system arrives at acceptable steady-state operating conditions after the contingencies. Usually, the security is addressed in two aspects: a) preventive actions applied to the pre-contingency system and b) corrective remedial actions (also termed special protection systems) taken following a credible contingency. Preventive actions usually restrict the tie-line interface power flows, the total generation output for certain plants or the angle difference across a particular path, which are conservative and can be costly. Therefore, corrective remedial action schemes can lead to less conservative transfer limits than the preventive action schemes.

Reliability rules require that the power system be able to withstand all single contingencies or N-1 outages without any RAS schemes. On the other hand, RAS schemes can be used effectively for mitigating N-2 outages or multiple contingencies. Remedial action schemes are triggered by the detection of the occurrence of a multiple contingency, and the RAS controller will then issue transfer trip signals to RAS control schemes. The RAS initiated controls include a) shedding remote generation, b) insertion or tripping of shunt and series capacitor/reactor banks, c) insertion of dynamic brakes, and d) load shedding.

Generator tripping and load shedding are two of most common control types for RAS, especially used for multiple line outage. In this case, the resulting higher power-flow on the remaining lines can push the system into transient instability unless the condition is corrected within the first swing of the transient response. Naturally, load tripping would be used as the last alternative if the other possible actions such as generation tripping or the insertion of shunt and series capacitor banks are not able to correct the problem. At the same time, we would like to minimize the amount of generation tripping that is initiated by the RAS scheme as an operations objective. Computing the minimum generation tripping amount to mitigate a contingency for a power system is nontrivial, since the tripping amount depends on various factors including the current operating conditions, the RAS controller action times, and the generator location. For the systems limited by transient stability, the tripping amount and the RAS action times are especially sensitive.

In the present day power system, the RAS tripping amounts are determined from detailed off-line stability studies, and the procedure is extremely time-consuming. Recently, different kinds of on-line dynamic security assessment methods have been proposed. These methods include: second-kick method based on energy concept [1, 2], Extended equal area criterion (EEAC) [3], data mining technique emergency control [4] and other methods [5,6].

In previous research at Washington State University, we have established that unstable limit cycles (ULS's) can play a crucial role in determining the transient stability of some power systems [7, 8]. Also, based on Hopf bifurcation theory, we had shown the relationship between the size of the ULC and the damping of the oscillatory mode [7,8]. In this paper, we propose a heuristic method for fast computation of "minimal" generation tripping amounts associated with RAS schemes, from pre- and post-contingency eigenvalue computations. We show that the proposed method is effective in computing the tripping amounts for mitigating a double line outage contingency in the Kundur two area test system [9].

2. ANALYSIS METHOD

In some power systems such as the western American interconnection WECC, interarea oscillatory modes are significant in determining the stability properties of the system. Clearly, the small-signal stability of a power system requires that all the modes have positive damping [9]. As we have shown in our earlier studies [7,8], ULC's associated with poorly damped interarea modes can anchor the transient stability boundary of the system (just like unstable equilibrium points or UEP's). Then, the size of the ULC is directly proportional to the positive damping level of the associated complex conjugate eigenvalues, when the damping factor is small and positive and when the Hopf bifurcation is "subcritical" [7,8].

By itself, the damping ratio of interarea modes can be an important factor for evaluating the system stability margin, especially for the large systems having inter-area modes, such as WECC system. In this paper, we try to find the relative change in the damping ratios of the interarea mode between the pre-fault and the post-fault systems to develop a rule for the RAS generation tripping amount. The eigenvalue computations are also fast even for large systems, and hence, the method is targeted towards online implementations. In our study, EPRI SSSP (Small Signal Stability Analysis) program is chosen as the main study tool and traditional nonlinear time domain simulation program ETMSP (Extended Transient and Midterm Stability Program) is also used in our study as a complementary tool to verify the results.

3. TEST SYSTEM DESCRIPTION

The tuning of RAS initiated generation tripping amounts is an important problem for the western American power system as well as for some Canadian utilities such as Hydro Quebec. In general, a large practical power system, such as WECC system, is chosen to study the power system dynamic performance. But the complexity of the large system adds the difficulty of analysis, and at the same time it may also obscure the fundamental nature of the problem. Therefore, we start with a small system in this paper, since it enables us to focus on the factors that have the significant effects on RAS.

Except for its complexity, WECC system is also a classical example of low frequency inter-area mode oscillation problem (0.25 Hz). The simple two-area system [9] has a somewhat similar topology as the WECC system in terms of sending and receiving areas and is a good candidate for getting insight into the mechanisms of the 0.25 Hz WECC mode. The Kundur system also has the mixture of inter-area and local modes, which matches our research requirement. Furthermore, this system is small enough to carry out extensive stability studies using both transient stability simulation tools as well as eigenvalue tools, so that the results cane compared..

It has been noted that under certain conditions, HVDC lines may contribute to oscillatory modes and voltage collapse phenomena during transient stability studies [9]. Therefore, in order to analyze HVDC effect on dynamics, the former test system is adjusted by adding a HVDC line parallel to the HVAC lines between the two areas, as shown in Fig. 1. Since the modified two-area system has the similar topology as WECC large power system, it is believed that the general conclusions drawn from the modified two-area system will be helpful for us to study the large power system transient characteristics.

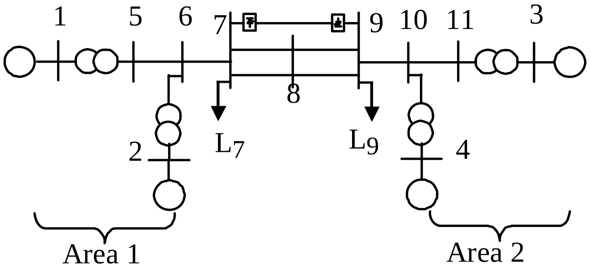

Fig. 1 Two area system with parallel DC-AC tie lines

4. REMEDIAL ACTION SCHEME BASED ON EIGENVALUE ANALYSIS

Using heuristic arguments noted above, this paper presents a new remedial action scheme based on the damping ratio of interarea oscillatory modes. This scheme assumes that we know what kind of contingency has occurred, such as line outage, etc., and proceeds to decide how much generation tripping would need to be initiated.

Based on extensive studies, the following rules have been developed for the two area test system. We would like to emphasize that the specific numbers in the rules would need to be tuned for other systems, and the criteria would likely have to be strengthened for application to large systems such as WECC. However, the rules proposed below outline the general philosophy of the proposed computational procedure, which we support with several simulations on the two area system. We will assume static load models for the loads in the system with typical mixed load types.

If the pre-contingency damping ratio of the inetrarea mode is above 3% and the corresponding post-contingency damping ratio is above 0.5%, no remedial action scheme is needed for this condition.

For normal cases, when the pre-contingency damping ratio is between 1.5% and 3%, and the post-contingency damping ratio is from 0.5% to –1.5%, remedial action scheme is necessary in the form of tripping generation in the sending area or/and load shedding in the receiving area. The minimal tripping amount is calculated based on the damping ratio difference between the pre-contingency and post-contingency damping levels of the inter-area mode. The tripping amount is evaluated as $P_{trip}=\alpha\times\mu \times \Delta d$. Here, Δd denotes the difference in damping levels of the interarea mode between the pre-contingency and post-contingency power-flow conditions, and is stated as a percentage. The parameter μ is defined as a "droop" like ratio of MW to % change in damping,

$$\mu = \text{ tripping amount in MW / change in damping ratio in units of } 0.1\% \qquad (1)$$

In other words, μ states how many MW's of generation will be tripped for each 0.1% change in the damping levels. The parameter μ is expected to be a constant for a specific system, and the ratio is somewhat different according to the load types and HVDC transfer amounts. But for a specific kind of load and fixed HVDC transfer amount, this ratio μ is an approximate constant value for the post-fault damping ratio between -1.5% and 0.5%. The coefficient factor α is between 0 and 1, and is introduced to tune the tripping amount for varied HVDC loading conditions. Then, the minimal tripping amount is represented by

$$P_{trip}=\alpha\times\mu\times\Delta d \qquad (2)$$

If the operation condition is known in advance, an appropriate coefficient factor α is chosen to obtain a better correction to the previous value; Otherwise α is set as 1, which gives a conservative value.

Action time (or RAS response time) is another important factor that should be taken into account for determining the minimal tripping. The action time is assumed to be between 0.1 sec and 0.25 sec. If the action time exceeds that limit, the tripping amount needs to increase correspondingly. In the test results, we will see that the case of purely constant power loads is a very special case in being the most severe in terms of stability constraints, and the heuristic rules stated above need to be modified somewhat for handling this special case.

If the pre-contingency damping ratio is below 1.5% (poorly positively damped) or if the post-contingency damping ratio is less than -1.5% (strong negative damping), we need to trip generation at the sending area, and also shed load at the receiving area simultaneously. In this case, the response time is very important. The quicker the RAS action, the smaller the minimal tripping amount and the better the stability performance.

5. TEST RESULTS

In this section, we will use the Kundur two area test system to analyze the different factors related to the remedial action scheme.

The study system is shown in Fig. 1. The MW power flow is normally from area 1 to area 2. All generators are modeled with exciters and governors. One PSS is included at generator 1. Contingencies associated with the transmission path are of primary concern in marking RAS decisions. For the HVDC, the rectifier side is represented using constant power and firing angle control, while the inverter side uses constant current and extinction angle control.

5.1 Effect of Loads on Generator Tripping Amount

In this subsection, we list the effect of several types of loads on the tripping amount and the action time.

- Constant impedance load (Table 1)
- Constant current load (Table 2)
- Constant power load (Table 3)
- Mixed load-1: 25% constant current, 50% constant power, 25% constant impedance load (Table 4)

HVDC line transfers a fixed 200MW from Area 1 to Area 2. Double lines outages (one of the circuits between buses 7-8, another is one of the circuit between buses 8-9) happen at 1.0 second. RAS action studied here is the tripping of partial generation at Generator 2. The results for minimal tripping amounts are computed using repeated simulations of the contingency in ETMSP.

Table 1 Effect of constant impedance load

Power flow (MW)	Pre-fault damping ratio	Post-fault damping ratio	RAS minimal tripping amounts (MW)	
			0.2 sec	1.0 sec
340	3.05%	0.77%	0	0
360	2.75%	0.18%	21	35
380	2.44%	-0.46%	56	70
400	2.12%	-1.11%	84	105
410	1.95%	-1.45%	105	126

Table 2 Effect of constant current load

Power flow (MW)	Pre-fault damping ratio	Post-fault damping ratio	RAS minimal tripping amounts (MW)	
			0.2 sec	1.0 sec
340	1.81%	0.60%	0	0
360	1.90%	0.45%	21	21
380	1.92%	0.16%	49	63
400	1.87%	-0.24%	77	98
420	1.74%	-0.79%	112	133
440	1.54%	-1.46%	147	168

Table 3 Effect of constant power load

Power flow (MW)	Pre-fault damping ratio	Post-fault damping ratio	RAS minimal tripping amounts (MW)	
			0.2 sec	1.0 sec
370	3.15%	1.29%	0	0
390	3.34%	0.07%	35	49
410	3.22%	-1.40%	77	91
420	3.03%	-2.35%	84	Unstable

Table 4 Effect of mixed type load 1

Power flow (MW)	Pre-fault damping ratio	Post-fault damping ratio	RAS minimal tripping amounts (MW)	
			0.2 sec	1.0 sec
360	1.76%	0.62%	0	0
380	1.89%	0.39%	28	42
400	1.92%	0.00%	63	84
420	1.86%	-0.59%	98	119
440	1.69%	-1.33%	140	161

We note the following observations from Tables 1-4.

- The damping levels of the interarea mode have a close relationship with the system stability. For double line outages, when the post-fault damping ratio is below certain value (say 0.5%), the transfer demand exceeds the transfer capacity and the system is tranient unstable without a rapid remedial action scheme. Under such conditions, as the interface MW power flow increases, the damping ratio decreases and tripping amount increase at the same time. This is because, as the damping ration decreases towards zero, the size of the ULC becomes smaller [7,8], and hence, the associated region of attraction for transient stability also decreases in size. Therefore, for the same RAS action time, more amount of generation should be tripped to maintain the system stable after the contingency.
- The ratio μ can be used to describe the generation tripping ratio per damping change. For certain kind of load, this ratio is nearly a constant value. For example, for the constant impedance load, the ratio μ is about 5 MW/0.1%; for constant current load, the ratio is about 5 MW/0.1%; for constant power load, the ratio μ is about 2 MW/0.1%; and for mixed type of load, this ratio λ is about 5 MW/0.1%. If the type of load is unknown before the contingency, we can use a conservative value 5.5 MW/0.1% for μ. In the next subsection 5.2, the conservative value of 5.5 MW per 0.1 % change in damping levels is used for computing the RA tripping amount from eigenvalue computations.
- The action time is also an important factor for deciding the minimal generation tripping amount, especially for the constant power load. Usually this action time should be within 0.25 sec. If the response time is slow for some reason, and if the fact is also known to the RAS controller, the tripping amounts should be increased correspondingly. When the action time is 1.0 sec, we need to use a μ value of about 7.5 MW per 0.1% damping change, as compared to a μ value of 5.5 MW per 0.1% damping change for the 0.25 sec action time. This observation is not always valid for the severe condition of a purely constant power load; for constant power load, when the response time is above 0.5 sec, tripping generator at Generator 2 alone is not enough to keep the system stable after the double line outage, for interface power flow is 420MW. This can be explained by two reasons: one is that constant power load is very sensitive; another reason is that HVDC link is parallel to the AC link and the DC link consumes about 40%-50% reactive power of comparable MW power it transfers. When double-line outage occurs, the AC voltage at converter sides will decrease and it also causes the decrease of reactive power supply for the HVDC link, possibly leading to commutation failures,.
- For double line outages, if the post-fault damping ratio is under -1.5%, tripping generator at the sending area alone may not keep the system stable after certain contingency. In this case, the system may need generation tripping and load shedding at the same time, especially for the constant power load. For instance, when the pre-fault flow is 460 MW, in order to maintain the system stable after double line outage, we need to trip generation at Generator 2 and also shed load at Bus 7 simultaneously, as shown in Table 6 for the constant power load. Such complex RAS schemes will be discussed in a later paper.

Table 5 Two kinds of RAS for special case

Power flow (MW)	Pre-fault damping ratio	Post-fault damping ratio	RAS minimal tripping amounts (MW)	
			0.2 sec	0.2 sec
460	1.66%	-6.72%	105 (gen) 71 (load)	140 (gen) 53 (load)

5.2 Comparison of Actual and Computed RAS Tripping Amounts

In the previous subsection, Tables 1 through 4 listed the minimal tripping amounts which are necessary for stabilizing the system, and these values were computed using extensive simulations of transient stability runs using ETMSP. In this subsection, we will compare the ETMSP based results with the eigenvalue based heuristic algorithm proposed in Section 4. For checking the effectiveness of the fast computational procedure, actual (ETMSP) and calculated (eigenvalue based) minimal tripping amounts for different kinds of loads are plotted in Figs. 2 to 6. If the load type is well-known ahead of the contingency, we can set a proper coefficient α a priori to better tune the computed values. Even if the load type is unknown, we can still get a feasible value, although the computed value is conservative as we see from figures.

The typical load type for a realistic power system is a mixed type instead of the basic types: pure constant impedance, pure constant power or pure constant current. The constant power type is not shown here since the rules need to be modified a little bit for this special case, and a purely constant power load is not realistic. Instead, we study two other two types of mixed load effect, as shown in Figs. 5 and 6.

- Mixed load 2: 50% constant current, 25% constant power, 25% constant impedance load
- Mixed load-3: 25% constant current, 25% constant power, 50% constant impedance load

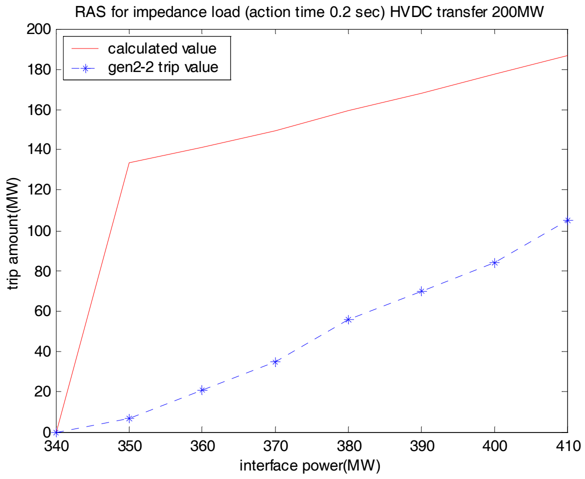

Fig. 2 Comparison for constant impedance load

In all the figures, the minimal RAS tripping amount that is computed using ETMSP is shown using dashed lines, while the tripping amount calculated using the eigenvalue rule is shown using solid lines. In Fig. 2, the tripping amount computed using the eigenvalue rule is always higher than the value from ETMSP studies, this indicating that the heuristic rule results in more conservative tripping amounts compared with the actual values. The difference between the two values also remains nominal under variations in the interface power-flow. For tie-line flows over 410 MW, the precontingency damping value of the interarea mode drops below 1.5% which would be unrealistic for nominal operation at the operating point. Hence, the results are not shown for higher power-flow cases.

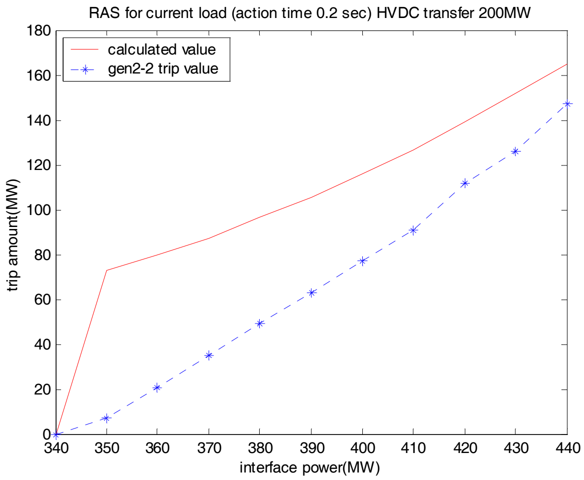

Fig. 3 Comparison for constant current load

In Fig. 3, the heuristic rule based results are less conservative, and are very close to ETMSP values. Similarly, the results also match very well for the mixed load types in Figs. 4, 5 and 6. It is also interesting the tripping amounts remain largely the same under three different mixed load types in Figs. 4, 5, and 6, which indicates that the RAS schemes can be expected to work very well, even when there is some uncertainty in the composition of the loads in the system. Our heuristic rule is also able to handle diverse mixture of loads and match well with the ETMSP results for stabilizing the double contingency.

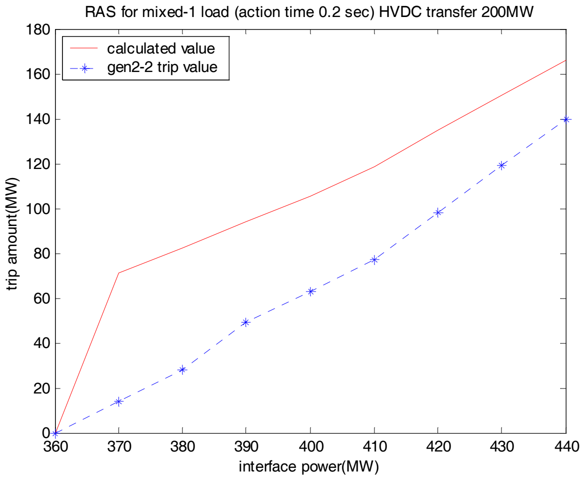

Fig. 4 Comparison for mixed load 1

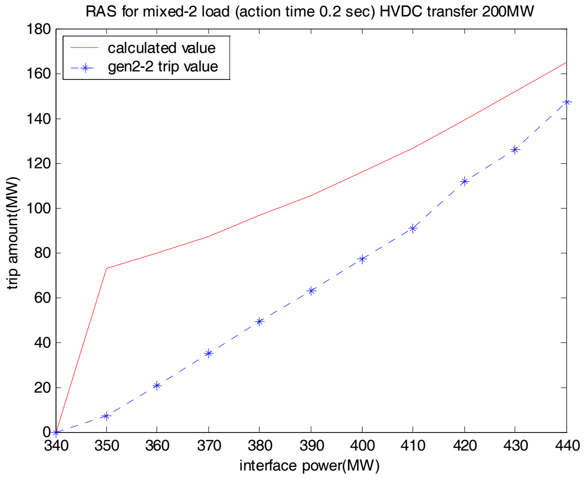

Fig. 5 Comparison for mixed load 2

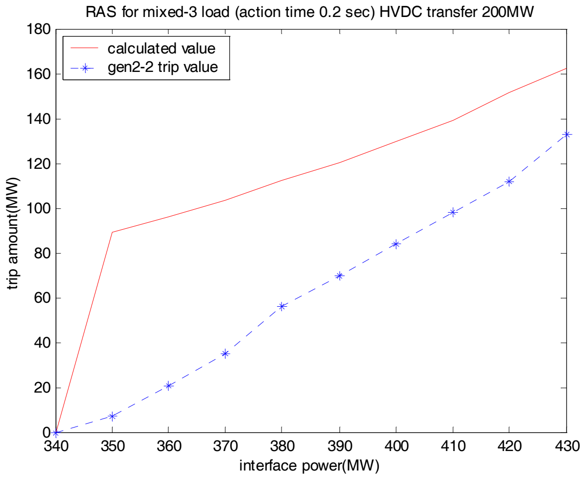

Fig. 6 Comparison for mixed load 3

5.3 Different HVDC Transfer Effect on RAS

It is well known that HVDC plays an important role in power system transient stability [9]. In this subsection, the HVDC MW flow is varied to study the impact on the double HVAC line outages contingency. In order to focus on the HVDC effect, AC line power flow is kept at a fixed value (190MW) while the DC flow is increased. Other assumptions are the same as the subsection 5.1. The effects of change in DC flow on the tripping amount are summarized in Table 6 and Fig. 7.

Table 6 Tripping amounts for different HVDC transfers for mixed load 1

Power flow (MW) (DC flow)	Pre-fault damping ratio	Post-fault damping ratio	RAS minimal tripping amount (MW)
390 (200)	1.92%	0.21%	49
410 (220)	2.10%	0.14%	56
430 (240)	2.22%	0.04%	63
450 (260)	2.31%	-0.10%	70
470 (280)	2.38%	-0.27%	77
490 (300)	2.40%	-0.49%	84

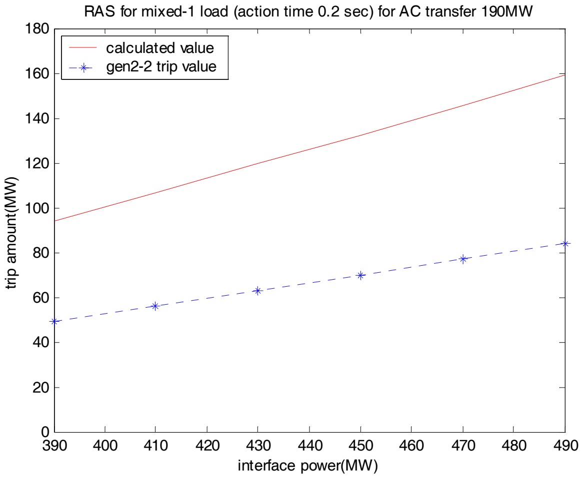

Fig. 7 Comparison for Mixed load 1

The results, shown in Fig. 7 and Table 6, lead to the following conclusions:

- When the HVDC transfer amount increases, the total interface transfer limit increases at the same time. However, even as the interface power increases, the AC line outage does not impact on stability as much as for the increase in AC MW flows studied in subsection 5.3. This is consistent with the general notion that DC power flow is more tolerant of AC line outages with regards to AC system stability.
- The difference between the damping ratios of the interarea mode for the pre-fault and post-fault cases increases as the DC power flow increases, which means that our proposed RAS scheme trips more MW's of generation, thus becoming more conservative. We can again use the ratio μ to represent the generation tripping amount. In reality, the ratio μ can be decreased a little while HVDC transfer amount increases. Using a constant value for μ (say 5.5) will give us a conservative estimate of the tripping amount as shown in Fig. 7.

6. CONCLUSIONS

Using heuristic methods, this paper presents a novel remedial action scheme, especially for choosing the minimal generation tripping amount, based on analyzing the relationship between the damping levels of the interarea mode for the pre-contingency and post-contingency power-flow scenarios. Effectiveness of this remedial action scheme is verified by comparing the results with those of transient stability studies using ETMSP. The results have been tested for different load types, and by changing AC as well DC transfer flows. The simulation results indicate that this remedial action scheme can provide a credible tripping amount although for certain cases, such as for the constant power load, the results are conservative.

Due to its simplicity and ease of implementation, this remedial action scheme is a useful tool for mitigating severe contingencies for on-line security assessment.

The main objective of this project is to develop fast on-line computational procedures for tuning the remedial action schemes under diverse operating conditions. Extending the results of this paper for a realistic large system promises to be a challenging task. Specifically, the method needs to be modified to handle a number of interarea modes, and also for handling UEP's on the transient stability boundary. These results can eventually be used for wide-area control schemes such as the one in proposed [10] for on-line modification of the generation tripping amounts and the tuning of other control parameters.

7. ACKNOWLEDGEMENTS

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9. APPENDIX: BLOCK DIAGRAMS OF GENERATOR CONTROL MODEL

Synchronous Generator parameters

$$\begin{gathered} R_a = 0.0025, X_d = 1.8, X_q = 1.7, X_d' = 0.3, X_q' = 0.55, X_d'' = 0.25 \\ X_q'' = 0.25, T_{d0}' = 8.0s, T_{q0}' = 0.4s, T_{d0}'' = 0.03s, T_{q0}'' = 0.05s \\ H_{1,4} = 6.175, H_{2,3} = 6.5 \end{gathered} \tag{3}$$

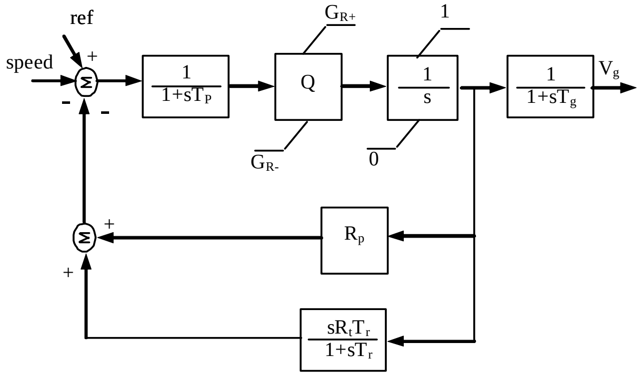

Fig. 8 IEEE G3 Mechanical-Hydraulic Governor Model

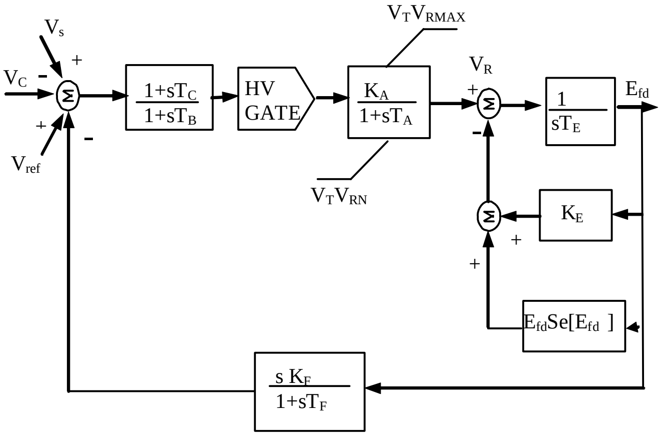

Fig. 9 IEEE DC1A Excitation System model

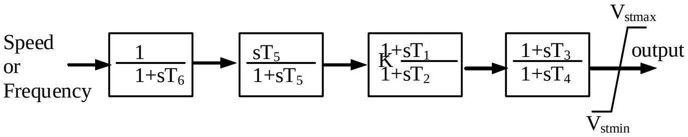

Fig. 10 IEEE PSS1A Power System Stabilizer Model

Load values and the reactive power supplied by shunt capactior banks at buses 7 and 9 are as follows:

Bus 7: P_L=967 MW, Q_L=100 MVar, Qc=300 MVar
Bus 9: P_L=1767 MW, Q_L=100 MVar, Qc=450 MVar

HVDC link parameters are:

V_{dr}=500 kV, R_{cr}=19.67 Ω, R_{ci}=19.77 Ω, and R_L=125 Ω.