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A METHODOLOGY TO ASSESS AND IMPROVE THE TRANSIENT STABILITY OF A LARGE-SCALE POWER SYSTEM

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ABSTRACT
Transient stability analysis and enhancement procedures for a practical large scale power system are covered in this paper. Generation and load scenarios are considered to observe various operating system behaviors. Static analysis is initially employed to investigate the static security performance under normal and contingency conditions. Based on a proposed index, the most severe contingencies are selected and ranked. Thereafter, detailed dynamic analysis is performed by modeling all basic components as well as various main and backup protection relays. Transient instability situations are detected either due to malfunctioning of relays or due to structural drawbacks of the network. Appropriate remedial actions are proposed and described.

KEY WORDS
Distance protection, relay malfunction, transient stability,

1. Introduction

A system is recognized to be transient stable if, following severe contingencies, remains in synchronism and the system integrity is preserved. A variety of methods for assessing the transient stability have been proposed, classified as time domain simulation, direct or transient energy function, and single machine equivalent (equal area) methods. Most practical approaches to transient stability analysis are based on the time domain simulation in which nonlinear equations are solved through well-defined numerical techniques [1]. Flexibility in detailed modeling of the generating units as well as other components are the distinguished advantages of this method. Such a procedure for a practical power system is reported in [3]. Direct method (or transient energy function) determines stability without explicitly solving the system differential equations [6]. In this method, while extensive simplifying assumptions are applied, the stability limits are detected based on a sensitivity analysis. Although the method is fast enough to be applied for real-time stability monitoring, an accurate analysis of the results is not possible. In equal-area based methods (the so called "extended equal-area criterion methods", too), the system is decomposed into two subsystems at fault clearing. One subsystem consists of the critical machines and the other of the remaining machines. Each subsystem is then transformed into an equivalent machine and the critical clearing angle is calculated through use of the equal area criterion. Since identification of critical machines in real power system is difficult, the machine equivalent method application is confined to small systems. A combination of the mentioned methods has been also used for transient stability analysis. For instance, [11] utilizes a hybrid approach in which time domain simulation is used for computing the actual system trajectory while direct method is used to derive a stability index for derivation of transient stability limits.

There are two approaches to measuring contingency severity in transient stability analysis. The first approach is based on the critical clearing time (CCT), measuring the maximum time the contingency can sustain without causing instability. In the second approach, the maximum power that the system can sustain without losing synchronism is calculated for a given clearing time. This criterion changes as generation pattern and/or loading condition change. Some references take account of the operating condition uncertainty by introducing probabilistic techniques. In [8] a risk based method is proposed to consider the uncertainty of contingency occurrence. The risk index is defined as a product of the probability of event occurrence and the consequences of the event. Generation rejection and load shedding to keep stability are considered as the event consequences.

In this work, time simulation of the governing differential equations and CCT approach are employed to analyze the transient stability of a practical large scale power system. The system under study is a regional utility of the high voltage transmission network, interconnecting the northern and the southern parts of the Iranian power grid. It transfers heavy power from the north to the south in hot seasons and in the opposite direction in the cold seasons. The total power consumption of the region is 2037 MW, while for the whole grid is 35244 MW. Recent incidents in the region have given rise to system-wide blackouts. This study aims at identifying the potential problems with the system under study and proposing the appropriate remedial actions. Initially, based on a proposed criterion, the most severe contingencies are determined. Thereafter, transient stability analysis is performed for the selected contingencies. The performance of the transmission system protection is evaluated and necessary remedial actions are then proposed and described.

The remainder of this paper is organized as follows. Section II describes the methodology of study including load-generation scenarios and contingency ranking index. A procedure for detecting protection system malfunction is also introduced in section II. Numerical results are presented in Section III. Section IV provides concluding remarks.

2. Methodology

2.1 Load-Generation Scenarios

For an actual power system, the grid is confronted by different operating conditions, in terms of, generation dispatch and loading levels. Theses are, initially, generated as operating scenarios. Three system loading scenarios including peak, medium, and light loads are considered. Network topology is assumed to remain unchanged in all scenarios. To create peak load base case, generation dispatch priority based on fuel cost, technical constraints of the generators, and other practical rules are taken into account. Nodal demands are modeled at the transmission level (buses) with their own estimated values. For medium load scenario, load and generation are accordingly adjusted with a weighting factor of 80 percent (a coefficient originating from system load duration curve). In creating light load scenario, the entire grid is first divided into external and internal parts, in terms of the system under study. For the external part, load and generation are adjusted with a weighting factor of 40 percent. To have a better estimate, in the internal part, nodal demands are forecasted from the following techniques and amalgamated then through equal weights [13]: (1) incidence factor method, and (2) exponential load growth method. Historical hourly load data (of transmission buses) over the past five years is then used to derive the necessary data.

2.2 Network Representation

The 2006 system model includes (1) synchronous generators and the associated excitation systems and prime movers, (2) interconnection transmission network including static loads, and (3) main and backup transmission line protection as well as generators out-of-step protections.

2.3 Analysis Procedure

2.3.1 Contingency ranking method

The static behavior is, first, analyzed for N-1 contingencies as well as the most probable, N-2 contingencies. A deterministic contingency selection method is adopted. An index, quantifying the severity of the operating constraints violation, is defined to rank the contingencies that bring about overload and/or voltage limit violations. This index is given by (1):

$$\mathrm{LVI} = \exp\left(1 - \frac{1}{\mathrm{VI} + \mathrm{LI}}\right) \tag{1}$$

where *VI* and *LI* are voltage and loading indices, respectively. *VI* index quantifies the violation of voltage limits and is defined as follows:

$$\mathrm{VI} = \mathrm{VI}_{230} + \mathrm{VI}_{400} \tag{2}$$

$$\mathrm{VI}_{230} = \sum_{j \in V_{230}} w_{230}[n_{v>1.05}.(V_j - 1.05)^2 + n_{v<0.95}.(V_j - 0.95)^2] \;, \; w_{230} = 0.575 \tag{3}$$

$$\mathrm{VI}_{400} = \sum_{j \in V_{400}} w_{400}[n_{v>1.05}.(V_j - 1.05)^2 + n_{v<0.95}.(V_j - 0.95)^2] \;, \; w_{400} = 1.0 \tag{4}$$

Similarly, *LI* index quantifies overloads by the following definition:

$$\mathrm{LI} = \frac{1}{N_{line}} . \sum_{j \in line_{230-400}} wl_k .[n_{s<80\%}.(\frac{S_j}{S_{thermal}})^2 + n_{80\%<s<100\%}.(\frac{S_j}{S_{thermal}}) + n_{s>100\%}.(\frac{S_j}{S_{thermal}})^2]$$

$$wl_{k=230} = 0.40 \;, \; wl_{k=400} = 0.60 \tag{5}$$

The notations used in (3)-(5) have the following meanings:

- V : bus voltage;
- $n_{v>1.05}$: no. of buses over 1.05 pu voltage limit;
- $n_{v<0.95}$: no. of buses under 0.95 pu voltage limit;
- w_{230} : 230 kV bus weighting factor;
- w_{400} : 400 kV bus weighting factor;
- N_{line} : no. of lines;
- wl_k : weighting factor of 230 kV and 400 kV lines;
- $(\frac{S_j}{S_{thermal}})$: line loading level with respect to thermal limit;
- $n_{s<80\%}$: no. of lines loaded under 80%.
- $n_{80\%<s<100\%}$:no of lines loaded in range (80, 100) %.
- $n_{s>100\%}$: no. of lines loaded over 100 %.

The value of the index, given by (1), lies within range [0,1]. As the value moves towards 1, the contingency is rated as more severe. A value of 0 corresponds to no violation of operation constraints.

2.3.2 Dynamic Simulation

Time simulation approach with critical clearing time (CCT) is utilized for transient stability analysis. For each contingency rated as critical, six possible cases are examined including symmetrical (three-phase fault) and unsymmetrical (single- and double- line to ground faults) faults at the line sending and receiving ends. A total number of 900 N-1 and N-2 faults are therefore simulated in three loading conditions.

2.3.3 Analysis of Transmission Protective Relaying

To detect the potential malfunctions of transmission line protection, static and dynamic analysis are carried out. The procedure employed to verify the relay performance is described next.

2.3.3.1 Static Relay Analysis

The transmission protection scheme employed comprises distance relaying both for the main and backup protections. Relays performance in response to the following faults are evaluated through performing fault analysis:

- Three-phase faults at 20% of the line length.
- Three-phase faults at 80% of the line length.

The rational behind these faults is to allow for the overlap of the first protective zone of the relay of the protected line, and the second protective zone of relay of the adjacent line. For each fault, the relays and the corresponding zones needed to be actuated following a given fault are determined and those really actuated following the fault, are identified. The relay malfunctions are thus classified as:

1-Case 1: Underreaching of the first protective zone;

2-Case 2: Overreaching of the first protective zone. Two situations are considered:

2-i) Correct operation of the second protective zone.

2-ii) Incorrect operation of the second protective zone.

To discriminate cases 2-i and 2-ii, further studies are done as follows. For a test fault leading to a malfunction categorized as Case 2, the first protective zones of all relays are blocked and the faults are then simulated and the operations of the second protective zone of all the relays are assessed. By comparing the operation of the second protective zone with what would normally be expected, the malfunctioning is categorized in either Case 2-i or Case 2-ii. The malfunctions rated as Case 2-ii, falls into one of the following categories:

3-Case 3: Underreaching of the second protective zone;

4-Case 4: Overreaching of the second protective zone;

All malfunctions are, accordingly, detected and identified for the main and backup protection relays by the proposed procedure. Fig. 1 shows the flowchart of the procedure.

2.3.3.2 Dynamic Relay Analysis

In this case, time simulation of the selected contingencies are carried out and relay behaviors in removing them are evaluated. Symmetrical (three-phase) fault at the line sending and receiving ends are considered in the dynamic simulations.

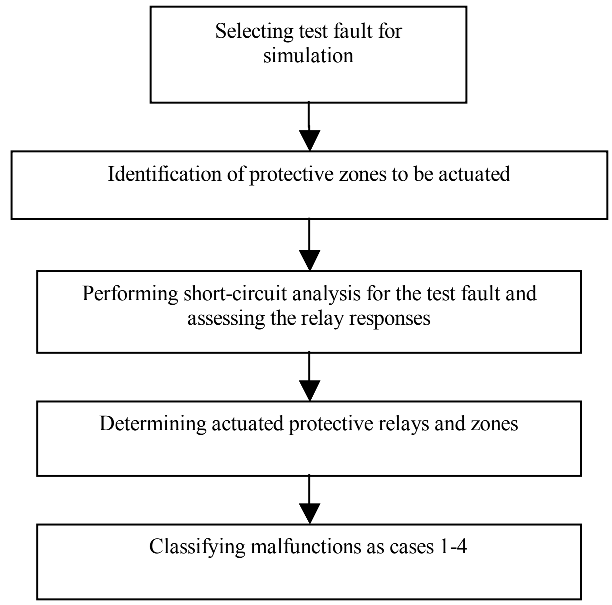

Fig. 1 Procedure of protective relay performance analysis

2.3.4 Improvement of Transient Stability

Base on results, the appropriate remedial actions either in terms of re-enforcement of network structure or relay retuning are examined. Re-enforcement of the network structure concerns both internal and external scenarios. Relay retuning is carried out for any of the out-of-tune distance relays both for the first and the second protective zones. These are described next.

2.3.4.1 Reinforcement of the Network Structure

Two scenarios were studied in detail. First scenario includes voltage regulation improvement of some high voltage buses using static voltage compensators (SVC). The candidate buses were adopted based on the CCT results of the critical contingencies starting either from or ending at candidate buses. In the second scenario, tie-line reinforcement with neighboring systems was examined. Several single alternatives were adopted and simulated. Each alternative was rated efficient as it could increase the CCT of the critical contingences above the threshold level. It was declined otherwise.

2.3.4.2 Protective Relay Retuning

According to static relay analysis, retuning of the first and the second zones were observed. For the first zone, 85% line coverage without time delay was adopted. For the second zone, 100% line coverage as well as 50% of the adjacent line were considered with its own predefined time response. To retune the second zone, current injections from all parts of the grid and mutual coupling effect of the parallel lines were taken into account. Also, the following points were examined:

a) The second zone reach should not be less than 120% of the line length.
b) The second zone reach should not be greater than 80% of the first zone of the adjacent line.
c) Should a transformer is connected to the line, the second relay zone should not protect the transformer.

For simplicity, retuning of the third zone was overlooked in this work.

3. Results

As already noted, the network under study is a part of the Iranian HV grid, the data of which is shown in Table I. Fig. 1 shows the simplifies single line diagram of the system under study, connoted to the main HV grid via tie lines.

Table 1
Data summery of system under study

peak demand (MW)	generation capacity (MW)/no. of units	transmission line length (km)	substation capacity (MVA)
2037	3200/8	3546	5065

As described in section II, initially the N-1 and N-2 contingencies are ranked based on LVI. The results are shown in Table II.

Table 2
Contingency ranking results

Contingency type	Loading condition	Contingency	LVI
N-1	Peak	tie-line to the west system (line no. 011)	0.65
	Medium	tie-line to the east system (line no. 010)	0.74
	Light	tie-line to the east system (line no. 010)	0.11
N-2	Peak	line originating from a generation bus (line no. 08)	0.84
	Medium	line originating from a generation bus (line no. 015)	0.83
	Light	line originating from a generation bus (line no. 015)	0.26

As shown, for each loading condition, at least one contingency is selected for further analysis. Thereafter, CCT calculations are carried out for the aforementioned contingencies, assumed critical if the associated CCT is less than 150 msec (based on the utility experience). As shown in Table III, for the peak loading condition, no CCT is over the limit while for the medium and low load conditions, the identified critical cases are tabulated.

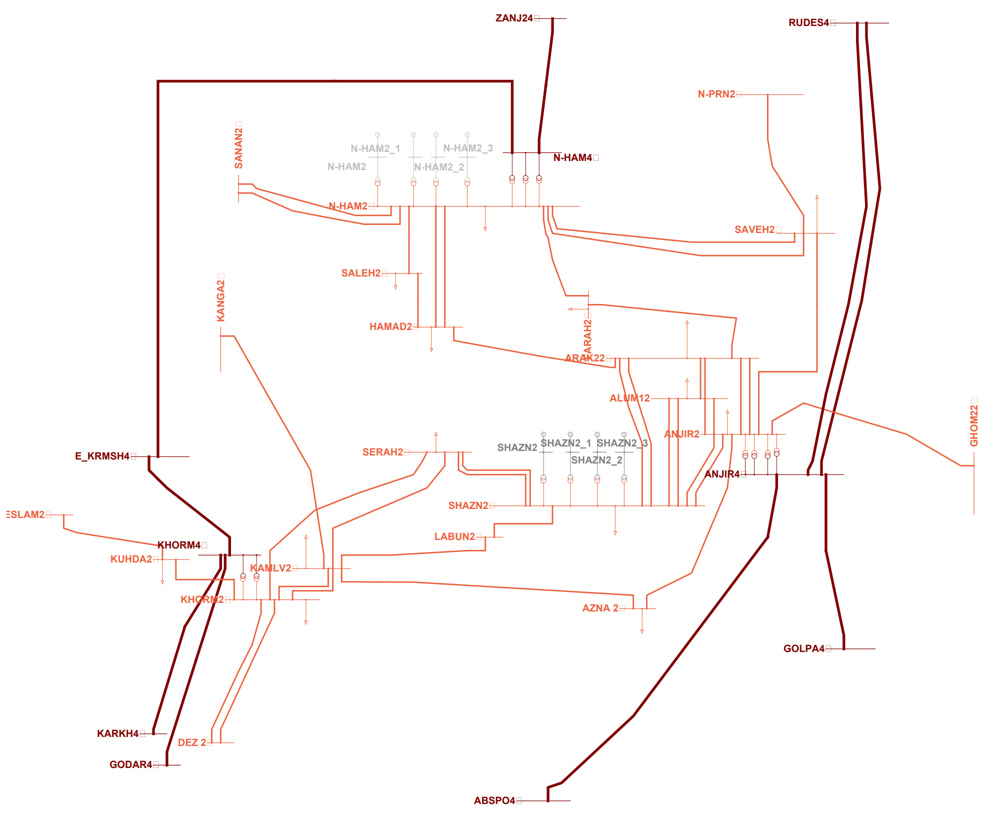

Fig. 2 Single line diagram of the system under consideration (connected to the main HV grid via tie lines)

Table 3
CCT results of critical contingencies (msec)

Loading condition	Line no./fault position	3-ph SC[#]	2-ph SC	1-ph SC
Peak	-	-	-	-
Medium	042/SE[*]	100	-	-
	040/SE	-	115	-
	038/SE	-	123	-
Light	042/SE	30	52	-
	038/SE	-	76	-
	040/SE	-	84	-
	042/RE[+]	92	115	-
	031/RE	-	131	-
	040/RE	-	139	-
	035/RE	-	139	-

[+] RE: receiving end   [*] SE: sending end
[#] SC: short circuit

To validate the results of Table III, further tests are carries out. For instance, Fig. 3 shows the rotor angle performance in response to a three phase fault at a typical bus for which CCT is calculated to be 341 msec. As demonstrated, the performance is stable for a fault clearing of 330 msec while unstable, for 420 msec. Out-of-step relays performances are also evaluated. A typical case is depicted in Fig. 4.

Regarding the relay performance, the malfunctions are initially identified as summarized in Table IV (see section II). For instance, in the second row it is shown that one malfunction of the first zone (zone 1) and three malfunctions of the second zone (zone 2) of the main relay on substation N_HAM2 are predicted (the protected line is a 230 kV one, connecting substation N_HAM2 to SAVEH2). For this case, the detailed results are shown in Table V. As a further test, in Fig. 5 time-distance diagram of a given transmission path is shown. As demonstrated, zone 1 of the relay on the beginning of this path (on substation ANJIR2) partly covers the adjacent line (line connecting buses AZNA2 to KAMLV2). Moreover, zone 2 of this relay overlaps with zone 2 of the next relay on the path (on substation AZNA2). In this way, wrong tuning of both relays is detected.

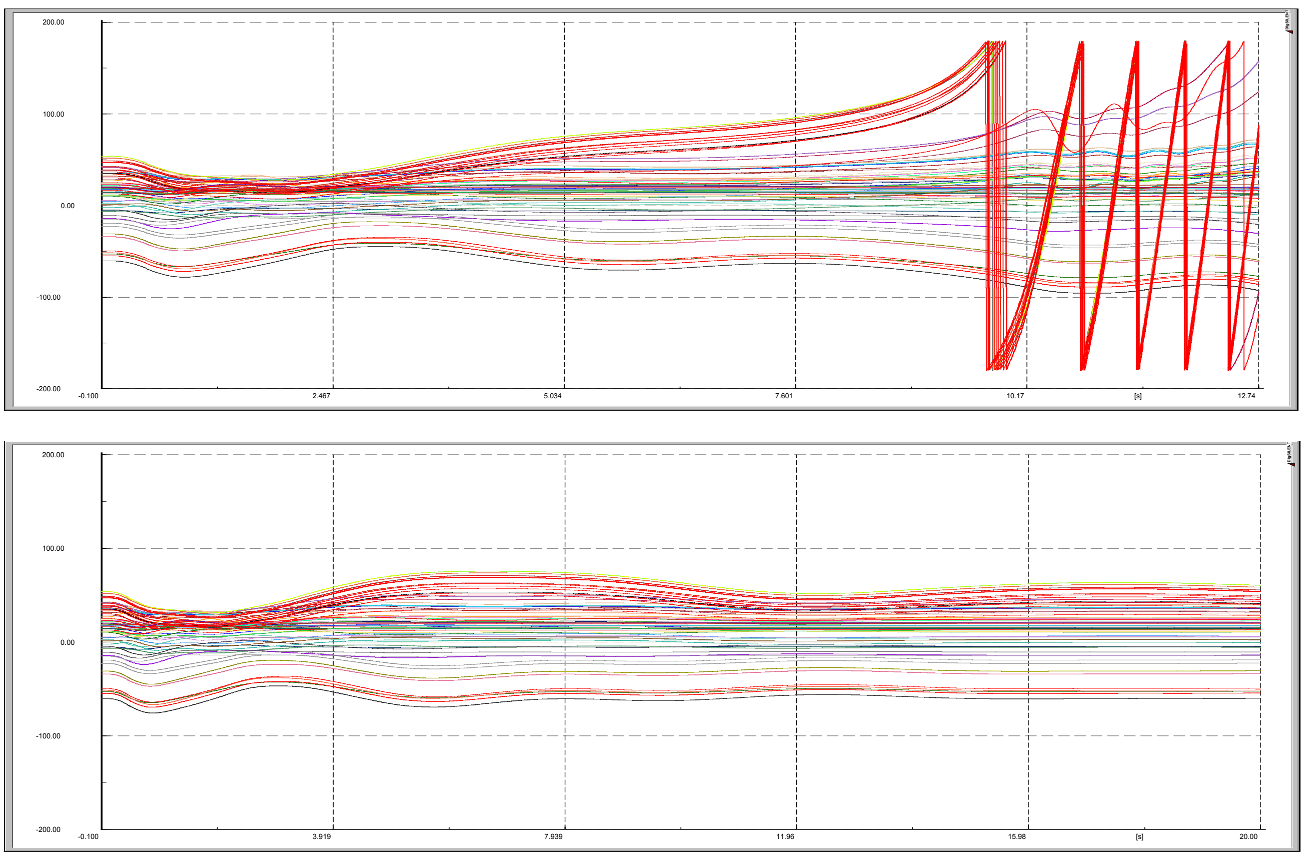

Fig. 3 CCTs results verification for a 3-ph fault: unstable (top) and stable (below), respectively as a result of untimely and timely fault clearing (x-axis: time in sec; y-axis: rotor angle in degree)

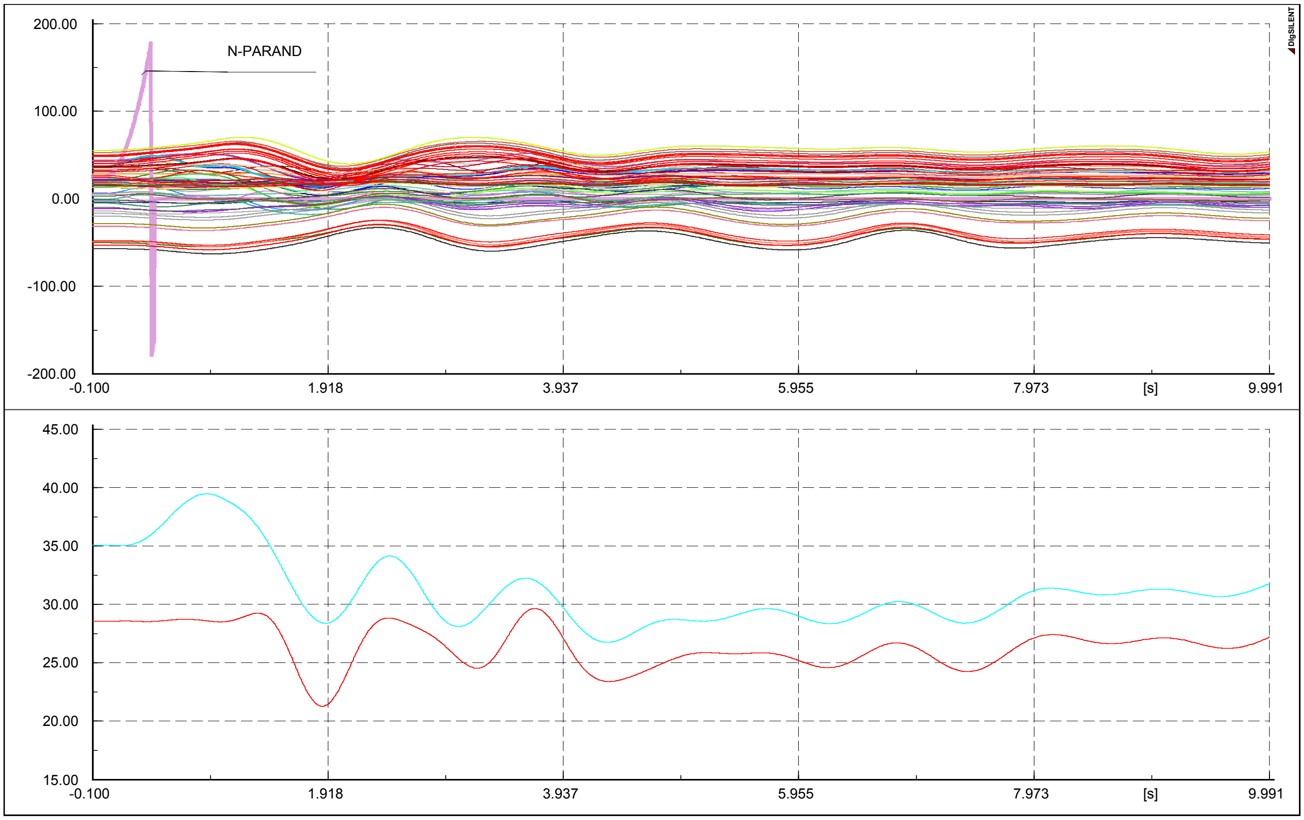

Fig. 4 Out-of-step relay operation in response to a 3-ph fault: disconnection of the unstable generator (marked on the top figure) and rotor angles of the generators of the system under consideration (below) (x-axis: time in sec; y-axis: rotor angle in degree)

Table 4
Identification of relay malfunctions: Typical brief results

no.	Relay Name	Classification of Malfunction			
		Case 1	Case 2	Case 3	Case 4
1	B_Dist_lne_ALUM12_ANJIR2_1_ALUM12	0	0	8	0
2	M_Dist_lne_N_HAM2_SAVEH2_2_N_HAM2	1	0	3	0
3	B_Dist_lne_ARAK22_FARAH2_1_FARAH2	1	0	7	0

B: Backup; M: Main; Dist: Distance; lne: Line;

Table 5
Identification of relay malfunction: Typical detailed results (corresponding to row 2 in Table IV)

no.	Relay Name	Case no.	Identified Malfunction
2	M_Dist_lne_N_HAM2_SAVEH2_2_N_HAM2	Case 1:	1- lne_N_HAM2_SAVEH2_2_80_N_HAM2
		Case 2:	-
		Case 3:	1- lne_ANJIR2_SAVEH2_1_80_ANJIR2 2- lne_SAVEH2_N_PRN2_1_20_SAVEH2 3- lne_SAVEH2_N_PRN2_1_20_SAVEH2
		Case 4:	-

As a dynamic simulation test, a three phase fault is applied to N_HAM2 substation (example). Relay response is shown in Fig. 6. It is seen from Fig. 6 that the fault is cleared with the actuation of zone 1 relay at N-HAM2 after 20 msec. However, since mho relay at SAVEH2 is not tuned properly for zone 2, its zone 3 clears the fault after 820 msec. Although delay clearing is observed, the stability performance is satisfactory.

As enhancement procedures, two approaches are investigated:

a) Structural including:
   - a-1) Considering SVC at some specific buses. This approach was carefully tested and the whole procedure repeated for contingencies. No significant effect was detected.
   - a-2) Considering HV transmission (tie) line reinforcement: As tested, reinforcement of some tie-lines with the neighboring systems, results in improving transient stability margins. For instance, CCT is increased from 150 msec to 300 msec, provided a 154 km (400 kV) line is added. It is evident that for the final decision the technical impact, both in terms of stability improvement and other measures should be evaluated against economical impact.

b) Relays retuning: Retuning of relays is the simplest economical approach. This approach is thoroughly performed for zone 1 and zone 2 of mho relays. As a result, new tuning for 320 zones 1 and zones 2 of relays are derived (both main and backup relays).

4. Conclusion

A procedure to transient stability analysis and enhancement of a practical power system was presented. Various operating conditions were observed in terms of load-generation scenarios. Static analysis was initially employed to investigate the static security performance under normal and contingency. Severe contingencies were selected and ranked based on a proposed static index. Also, malfunctions of transmission protection system were detected through a proposed procedure. Thereafter, detailed dynamic analysis was performed by modeling all basic components as well as various main and backup protection relays. Transient instability situations were detected either due to malfunctioning of relays or due to structural drawbacks of the network. Appropriate remedial actions in terms of structural measures and relays retuning were proposed and described.

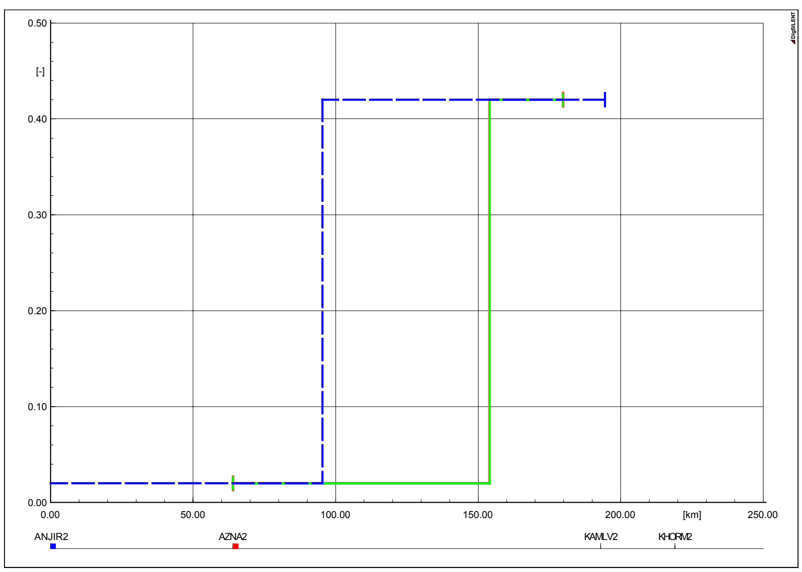

Fig. 5 Time-distance diagram of relay on path ANJIR2-AZNA2-KAMLV2: Existing relay tuning and the identified [incorrect] overlap of the protective zones (x-axis: distance in km; y-axis: time in sec)

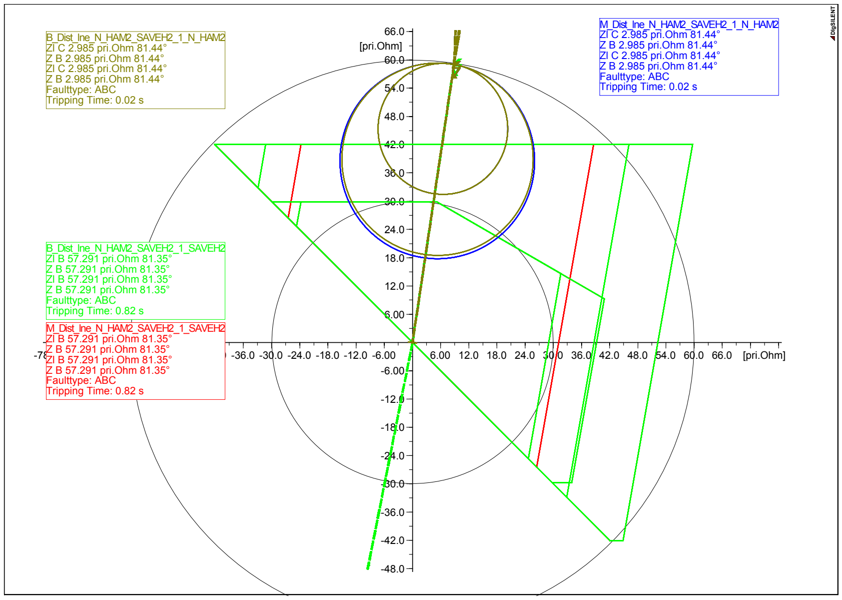

Fig. 6 Polar characteristics of relays protecting line N_HAM2-SAVEH2 in response to a 3-ph fault

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