Methods to Improve Transient Stability of Low-Inertia Synchronous Machines

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***Abstract*— This paper highlights the factors influencing transient stability of synchronous machines. Further, it investigates the role of various excitation systems and the power system stabilizer on the machines' first swing stability, by modeling a single-machine-infinite bus (SMIB) 60 Hz test system on ETAP. Results of the findings are summarized and evaluated. Finally, methods of improving the transient stability are also discussed.**

***Keywords*—transient stability, first swing stability, fault ride through, excitation system, power system stabilizer, rotor angle, inertia, damping**

I. Introduction

Transient stability falls under the broader category of rotor angle stability, as shown in Figure 1, in the power system stability classifications. The transient stability or instability of a power system is determined by how the system responds to a severe disturbance. A system is considered to be transiently stable if it can survive the most onerous initial disturbance, which is typically defined as a 3-phase fault occurring near the high side bus of the largest generating station in the system. It is considered to be transiently unstable if it cannot survive such an event. Transient stability is often referred to as first swing stability as the instability occurs during the first angle swing. Many power systems restrict their MW transfers due to transient stability concerns. Generally, those power systems with long transmission lines and remote generation are most susceptible to transient instability [1].

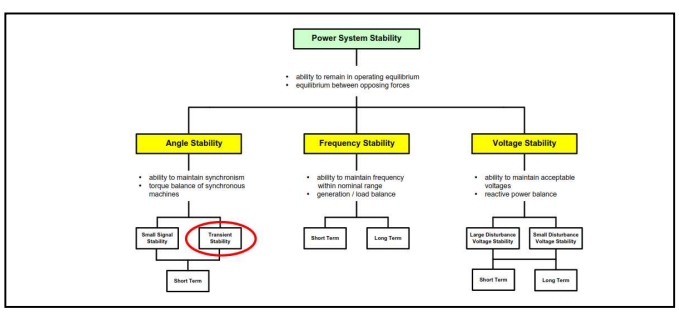

Fig. 1. Power System Stability Classifications

Throughout the world, and particularly in North America and Europe, System Operators are diligently enforcing grid code requirements. As such, many grid codes clearly define the fault ride through (FRT) requirements at the point of interconnection (POI) for synchronous machines, which becomes obligatory for the generation equipment manufacturers to meet or exceed. These FRT requirements have direct correlation with the transient stability of the synchronous machines in the system. For instance, in North America, NERC PRC-024-2 mandates the FRT capability of synchronous machines to meet or exceed 150 milliseconds (at 0 voltage). A machine that becomes transiently unstable following a large disturbance will trip on "out of step", and this may lead to other cascading system-wide events.

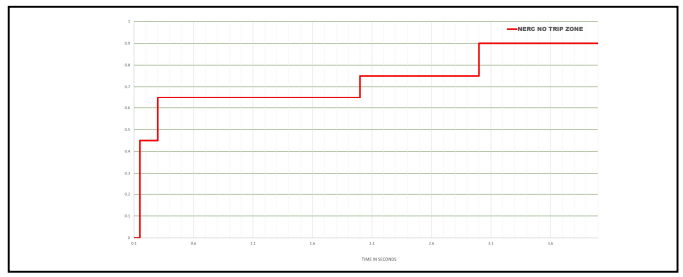

Fig. 2. Typical FRT Profile for Synchronous Machines mandated in N. America

Synchronous machines play a decisive role in the power system stability because during and after disturbances their rotor angles will oscillate to cause power flow oscillations in the system. Depending on the level of these oscillations, the electromechanical equilibrium in the system could be destroyed and the instability could occur. The Torque and Swing Equations, presented below in Eq. 1 and 2 respectively, govern the transient stability phenomenon in any power system. The torque equation defines the relationship between the mechanical shaft torque, the stator voltage, the excitation system, and the rotor angle. Changes in any one of them will cause the rotor angle to readjust itself to a new position. On the other hand, the swing equation shows that the solution of the rotor angle is a function of balance between the mechanical power input and electrical power output. Any change in the system that breaks this balance will cause the rotor angle to undergo a transient and reach a new position in an oscillatory manner [3].

$$T = \frac{\pi P^2}{8} \emptyset_{air} F_r \sin\delta \text{ (Eq. 1)}$$

Where,

T = Mechanical shaft torque

P = Number of poles

$\emptyset_{air}$ = Air-gap flux

F_r = Rotor field MMF

δ = Power (rotor) angle

$$M\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = P_{mech} - P_{elec} \text{ (Eq. 2)}$$

Where,

M = Inertia constant

D = Damping constant

P_{mech} = Input mechanical power

P_{elec} = Output electrical power

II. Factors Influencing Transient Stability

There are numerous elements that impact transient (or first-swing) stability of a synchronous machine in a power system. The dominant factors are highlighted and discussed below.

1. System transfer reactance: All other system parameters remaining unchanged, a lower system reactance value will improve the transient stability, and this can be inferred from the following power swing equation. Incidentally, reduction of system transfer reactance also raises system voltage profile.

   $$P_T = \frac{V_1 V_2}{X}\sin\delta \text{ (Eq. 3)}$$

   Where,

   P_T = Power transferred between Bus 1 and 2

   V_1 = Voltage phasor at Bus 1

   V_2 = Voltage phasor at Bus 2

   δ = Relative rotor angle between Bus 1 and 2

2. Grid strength: This refers to the ability of the transmission system to maintain strong synchronizing forces during the transient initiated by a disturbance. Typically, a "strong" grid yields better transient stability as compared to a "weak" grid, assuming all other system parameters remain unchanged.

3. Synchronizing power: It is the measure of the stiffness between the rotor and the stator coupling. It is directly proportional to the main field voltage, and as such, an over-excited machine is stiffer than an under-excited machine. Shunt reactor banks and synchronous condensers are sometimes used to allow the machine to permanently operate in over-excited (lagging power factor) region, which results in improved transient performance.

4. Moment of inertia: The moment of inertia (WR^2) tends to have a significant impact on the transient stability. All other parameters remaining unchanged, a heavier machine has a better chance of surviving a large disturbance and remain in synchronism, relative to a lighter machine. Inserting flywheels on the turbine-generator shaft line is a technique commonly used to increase the moment of inertia for light-weight machines. However, increasing the moment of inertia may have an undesirable effect of sluggish response of the speed governor loop.

5. Damping: The value used for D, presented in Eq. 2, depends greatly on the kind of generator model used and particularly on the modeling of the amortisseur windings [4]. For round-rotor machines, this value is typically 0.

6. System protection: Fast action of high-speed relaying and breaker trip/reclose during large disturbances typically improves the transient stability of machine. The objective is to detect faults and isolate faulted sections of the transmission network very quickly with minimum disruption. Despite high-speed protection, most grid codes still mandate a minimum FRT duration.

7. MW loading/unloading: Especially for light-weight machines, the transient stability is inversely proportional to their loading. In other words, these machines typically have a better chance of achieving transient stability if they are partially loaded as opposed to fully loaded (prior to the disturbance). Similarly, during the disturbance, the ability of the governor to un-load quickly also plays an important role in maintaining the transient stability. This phenomenon is further discussed in Section VI.

8. Excitation System and Power System Stabilizer: This is discussed in detail in the following sections.

III. Role of the Excitation System

As discussed in the earlier sections, in the transient stability problem the performance of the power system when subjected to severe impacts is studied. The concern is whether the system is able to maintain synchronism during and following these disturbances. The period of interest is relatively short (at most a few seconds), with the first swing being of primary importance. In this period the generator is suddenly subjected to an appreciable change in output power causing its rotor to speed up (or slow down) at a rate large enough to threaten loss of synchronism. For the purposes of this discussion, it is assumed that the power supplied by the prime movers does not change in the period of interest, i.e. no governor response is considered. Therefore, the effect of excitation control on this type of transient depends upon its ability to help the generator maintain its output power in the period of interest, by holding the flux level of the synchronous machine. Modern fast excitation systems are usually acknowledged to be beneficial to transient stability following large impacts by driving the field to ceiling without delay. With the help of fast transient forcing of excitation and the boost of internal machine flux, the electrical power output of the machine may be increased during the first swing compared to the results obtainable with a slow exciter. This reduces the accelerating power and results in improved transient performance [5].

However, except for transient stability studies involving faults with long clearing times (or stuck breakers), the effect of the excitation system on the severity of the first swing is relatively small. That is, a very fast, high-response excitation system will usually reduce the first swing by only a few degrees or will increase the generator transient stability power limit (for a given fault) by only a few percent [5].

IV. Test System & Study Methodology

The discussions presented in the literature highlighted in Section III were tested on a SMIB system shown in Figure 3. Equipment and system related parameters are also presented below.

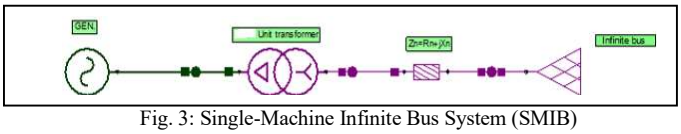

Fig. 3: Single-Machine Infinite Bus System (SMIB)

1. Total Turbine-generator drive train Inertia (H) Constant: 1.375
2. Generator ratings: 47.8 MVA, 0.85 Lagging Power Factor, 13.8kV, 60 Hz, 2-pole, Round Rotor
3. Grid short-circuit strength: 30 kA at 138 kV
4. Generator Step Up Transformer (GSUT) ratings: YNd1, 13.8 kV/138 kV, Z = 15% at 80 MVA
5. Governor action: Fixed (i.e. No action)
6. Generator in Voltage Control mode
7. Initial MW load setpoint: 35 MW
8. Bolted 3-phase fault at the POI (i.e. 138 kV HV Bus)
9. Target: FRT of 150 milliseconds (per NERC PRC-024)
10. Transient stability simulations are performed considering the POI at 0.95 leading power factor

Additionally, the following excitation systems have been considered, and their respective datasets are presented in Tables I to IV.

1. Fixed
2. Brushless – IEEE 421.5 AC7B (simulations performed with 3 different datasets). Refer to Figure 4 below.

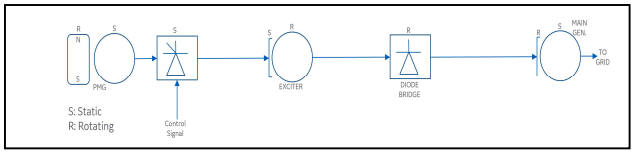

Fig. 4: Brushless Excitation System

3. Static – IEEE 421.5 ST1A (simulations performed with 2 different datasets) and IEEE 421.5 ST2A. Refer to Figure 5 below.

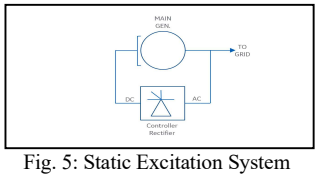

Fig. 5: Static Excitation System

4. Power System Stabilizer (PSS) – IEEE 421.5 PSS2A (used in conjunction with AC7B-3).

TABLE I. BRUSHLESS EXCITATION SYSTEM PARAMETERS

	FIXED	AC7B-1	AC7B-2	AC7B-3
VAmax	N/A	1	10	1
VAmin		-0.95	0	-0.99
VRmax		5.79	10	13.55
VRmin		-5.79	0	0
VEmin		-20	-20	-1
VFEmax		6.9	99	55.26
VUEL		-3	-3	-3
E1		6.3	4.5	12.6
SE1		0.44	1.5	0.125
E2		3.02	3.38	9.45
SE2		0.075	1.36	0.042
KPR		4.24	170	40
KIR		4.24	130	40
KDR		0	60	0
KPA		65.36	1	1.023
KIA		59.69	0	1.203
KP		4.96	1	55.23
KL		10	0	10
KE		1	1	1
KD		0.02	0	1.03
KF1		0.212	0	0
KF2		0	0	1
KF3		0	0	0
KC		0.18	0	0.2
TE		1.1	1	0.85
TF		0	0	1
TDR		0	0.03	0
TR		0	0	0.01
RC		0	0	0
XC		0	0	0

TABLE II. POWER SYSTEM STABILIZER PSS2A PARAMETERS

	PSS2A
KS1	6
KS2	1.07
KS3	1
VSTMax	0.1
VSTMin	-0.1
VTMin	0
TDR	0
Tw1	3
Tw2	3
Tw3	3
Tw4	100

N	1
M	5
T1	0.04
T2	0.01
T3	0.3
T4	0.01
T6	0
T7	3
T8	0.5
T9	0.1
Input #1	Electric Power
Input #2	Speed

TABLE III. STATIC ST1A EXCITATION SYSTEM PARAMETERS

	ST1A-1	**ST1A-2**
VAmax	500	500
VAmin	-500	-500
VImax	10	999
VImin	-10	-999
VRmax	6.43	7.8
VRmin	-6	-6.7
VUEL	-3	-3
VOEL	3	3
KA	210	190
KC	0.038	0.08
KF	0	0
KLR	4.54	0
ILR	4.4	0
TB	1	10
TB1	0	0
TC	1	1
TC1	0	0
TA	0	0
TF	0	1
TR	0.02	0.04
RC	0	0
XC	0	0

TABLE IV. STATIC ST2A EXCITATION SYSTEM PARAMETERS

	ST2A
VRmax	1
VRmin	0
VUEL	-3
Efdmax	2.75
KA	120
KC	1.82
KE	1
KF	0.05
KI	8
KP	4.88
TA	0.15
TE	0.5
TF	1
TR	0

V. RESULTS

The study results are presented in Figures 6 to 8. Interestingly, the excitation systems and the PSS had no meaningful impact on the first swing stability of the test system. In all cases, the maximum clearing time achieved was approximately 135 milliseconds. These results are consistent with the literature [5] presented and discussed in Section III. Based on Figure 6, it is evident that the effect of the excitation system (Brushless or Static) on the first swing of the generator rotor angle is limited (with or without PSS). The difference between the maximum and minimum swing is approximately 4 degrees, which is insufficient to influence the first swing stability of the machine, because its electrical output (i.e. P_{elec} in Eq. 2) does not increase to the requisite level during the first swing. This can be attributed to the inherent latency in ramping of the voltage on the generator field windings and boosting of internal machine flux in spite of fast transient forcing of excitation, as illustrated on Figure 7, and subsequently the effect on the generator terminal voltage is also very minimal during the first swing (shown on Figure 8). After fault clearing, recovery to healthy terminal voltage (i.e. 80%) takes approximately 265 milliseconds (AC7B-1) to 365 milliseconds (AC7B-2).

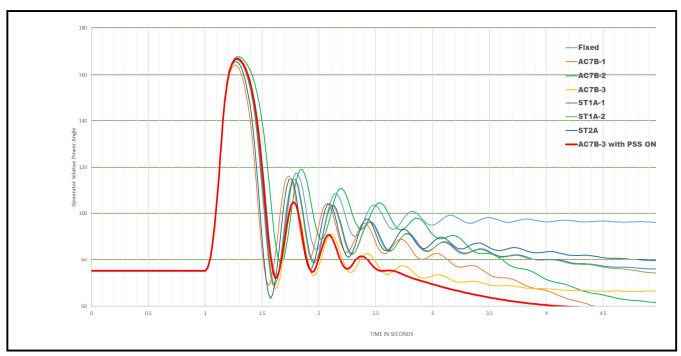

Fig. 6: Generator Relative Rotor Angle (in degrees) vs Time

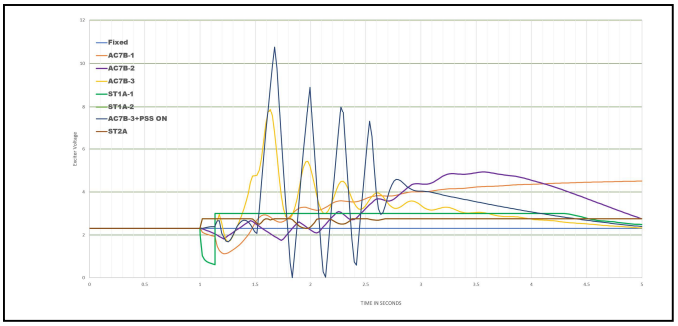

Fig. 7: Generator Exciter Voltage (in per unit) vs Time

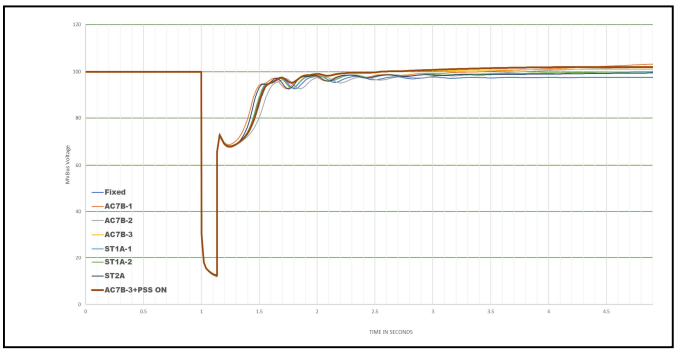

Fig. 8: Generator Bus Voltage (in %) vs Time

VI. Summary and Recommendations

The previous section studied the role of various excitation systems and the PSS on the transient or first swing stability of synchronous machines, by modeling a SMIB 60Hz test system on ETAP. No improvements with regards to first swing stability were observed, which is consistent with [5]. However, there are several measures that can be considered in order to increase the transient stability limits of a synchronous machine. Salient measures are:

1. reduction in the overall system reactance. Lower GSUT impedance may be considered in this case. Further, a lower direct axis transient reactance and higher direct axis open circuit time constant of the synchronous machine may also be considered in this regard.
2. adding shunt reactor banks and/or synchronous condensers to force the machine to permanently operate in the over-excited region, thereby increasing the synchronizing power.
3. adding flywheels to the turbine-generator shaft line, to increase the moment of inertia and the H constant.
4. high-speed protection to facilitate fast clearing of faults
5. fast unloading of the machine during disturbance through governor action.

Each of these aforementioned remedies will require careful consideration both from economic as well as technical feasibility standpoints. In most cases, remedies 1-4 mentioned above may be unrealistic given their impact on the overall plant design, adverse side effects in some cases, and of course the associated cost. As part of this study, remedy #5 was pursued further. In order to achieve 150 milliseconds of FRT with the boundary conditions stipulated in Section IV, the machine must unload from 35 MW to approximately 18 MW within approximately the first 100 milliseconds after fault initiation through governor action (P_{mech} in Eq. 2). This translates to an unloading ramp rate of 170 MW/second (refer to Eq. 5 below). This quickly brings down the accelerating power and results in improved transient performance. For relative comparison, the results presented in Section V were based on an unloading ramp rate of 0 MW/s. Depending on system latency for fault detection, the actual unloading ramp rate could be 200-250 MW/second. This assumes that the fuel supply systems can be modulated at a speed that is commensurate with this expected ramp rate. Early detection of faults on the HV side of the GSUT also becomes crucial in order to minimize the system latency. The sooner the fault is detected, the sooner the governor action comes into effect, which allows the machine that much more time to de-load and remain stable, as shown on Eq. 4 below.

$$TD = EED + UD \quad \text{(Eq. 4)}$$

Where,

TD = Total Duration (in seconds)

EED = Early Electrical Detection (in seconds)

UD = Unloading Duration (in seconds)

$$URR = \frac{\Delta P}{UD} \quad \text{(Eq. 5)}$$

Where,

URR = Unloading Ramp Rate in MW/second

ΔP = (Initial MW at pre-fault) – (Target MW during fault)

VII. Conclusion

This paper highlighted the factors influencing transient stability of synchronous machines. It also investigated the role of various excitation systems and the PSS on the machines' first swing stability, by modeling a SMIB 60 Hz test system. Results of the findings were summarized and evaluated. Several methods of improving the transient stability were discussed. There remains significant scope for future work in this regard.

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