ENGINEER - Vol. LIX, No. 02, pp. [155-164], 2026

DOI: https://doi.org/10.4038/engineer.v59i2.7758

Experimental Determination of Synchronous Generator Saturation Factors using AVR Open-Circuit Testing

I.P.T.P.D.B. Nikaweratiya, L.A.H.S. Perera, J.P. Karunadasa and R.R.T.W.M.R.A.I. Madawala

Abstract: Accurate modelling of power system components is essential for reliable power system analysis, particularly in excitation system and AVR studies. While IEEE Std. 421.5–2016 defines how generator saturation factors should be obtained, practical modelling often continues to use standard or factory data, with limited measurement-based updates for aged generators in actual service. This is a key research gap, since saturation characteristics may vary over time due to aging and operating stresses. Accordingly, this study presents the experimental determination of saturation factors of a 20 MW synchronous generator at Sapugaskanda Power Station, Sri Lanka. An open-circuit test was selected because it provides the direct terminal voltage–field current characteristic required for IEEE-based saturation-factor calculation. With the AVR in manual mode, the field current was varied within specified protection limits, and steady-state terminal voltage and field current were recorded using a Hioki data acquisition system and analysed in Excel to construct the open-circuit saturation curve and air-gap line. The saturation factors at 1.0 pu and 1.2 pu were then calculated using the IEEE method. The results provide updated field-based inputs for improved AVR and exciter model accuracy.

Keywords: Synchronous generator, saturation factor, open-circuit test, excitation system modelling, Automatic Voltage Regulator (AVR), parameter validation, power system stability

1. Introduction

Accurate modelling of synchronous generators forms the cornerstone of modern-day power system stability and dynamic performance studies. With generators remaining the primary source of electrical power in interconnected networks, their modelling on simulation software packages needs to mimic both steady-state and transient behaviour to a very high degree of accuracy. Among many of the parameters influencing generator performance, magnetic saturation is really important, especially in AVR and excitation control system operations [1].

Saturation is the nonlinear relationship between induced terminal voltage and generator field current, and it becomes particularly significant at high excitation levels, for example during forced excitation by the AVR after a voltage dip, during sustained overexcited reactive power operation, or when the generator is tested near its overvoltage limit under open-circuit conditions. If saturation effects are not modelled accurately, the resulting studies may produce incorrect conclusions on stability margins, transient behaviour, and excitation control performance.

The per-unit convention is usually employed in power system analyses to make the electrical values unity-based in order to make models invariant with respect to actual machine ratings. Generator saturation is thus quantified using saturation factors, which are obtained, typically, from the open-circuit characteristic curve of the generator and its corresponding air-gap line [2].

Mr. I.P.T.P.D.B. Nikaweratiya, BSc. Eng. (Hons) (KDU), Dept. of Electrical, Electronics & Telecommunication Engineering, General Sir John Kotelawala Defence University
Email: 38-eng-0118@kdu.ac.lk
https://orcid.org/0009-0000-0717-0377
Mr. L.A.H.S. Perera, BSc. Eng. (Hons) (KDU), Dept. of Electrical, Electronics & Telecommunication Engineering, General Sir John Kotelawala Defence University
Email: 38-eng-0154@kdu.ac.lk
https://orcid.org/0009-0009-1478-0769
Eng. (Prof.) J.P. Karunadasa, C.Eng, MIE(SL), MIEEE, BSc. Eng. (Hons) (Moratuwa), MSc (UMIST), PhD (UMIST), Associate Professor in Electrical Engineering, University of Moratuwa, Sri Lanka
Email: karunadasaj@uom.lk
https://orcid.org/0000-0003-4678-0286
Eng R.R.T.W.M.R.A.I. Madawala, C.Eng, MIE(SL), MSc (Moratuwa), Chief Engineer (Assets Management, Thermal Generation, Ceylon Electricity Board
Email: aimadawala@gmail.com
https://orcid.org/0009-0000-1932-6244

The study provides a recommended method of building and calculating these saturation factors. On the standard [3], the field current required to produce a given terminal voltage on the open-circuit characteristic is measured against the theoretical air-gap line, and the difference is used to build a saturation function. Two standard points, 1.0 pu and 1.2 pu of terminal voltage, are typically used to determine saturation factors that are then applied in generator and excitation system models.

The typical open-circuit saturation characteristic, as shown in Figure 1 as defined in IEEE Std 421.5-2016, is utilized to show the typical nonlinear synchronous generator response. This typical curve is utilized as the reference point for the computation of saturation factors, which are important in accurate modeling of the generator and excitation system dynamics.

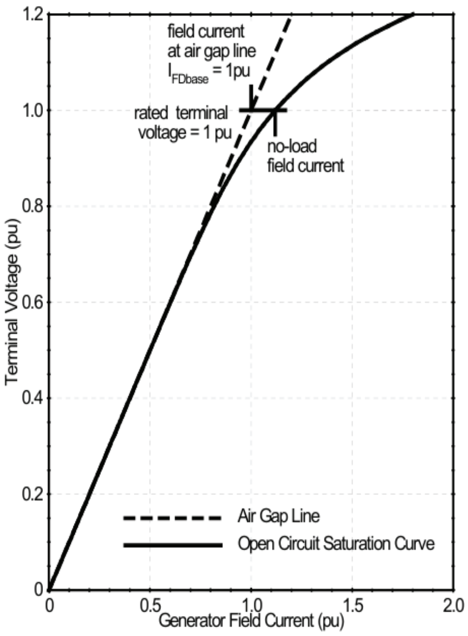

Figure 1 – Generator open-circuit saturation characteristics [1]

Several researchers have commented on the necessity of generator saturation modelling to provide simulation of dynamic responses. Study [4] commented that the neglect of saturation in synchronous machine models would cause transient stability evaluation errors. Study [5] also pointed out that the performance of the excitation system depends largely on good generator saturation representation because the AVR is in continuous interaction with the generator terminal voltage. Subsequent work, such as the IEEE working group documents, has left it to the standard for the inclusion of saturation functions in excitation models, like common AC1C and DC models [6].

Experimentally, the open-circuit test remains the most reliable method of measuring generator saturation. The test involves disconnecting the generator from the grid, operating the AVR in manual mode so that excitation is controlled directly rather than by automatic terminal-voltage regulation, and varying the field current to record the corresponding terminal voltages. The measured voltage–current pairs are plotted to obtain the open-circuit characteristic and build the air-gap line. The saturation factors could then be determined from this.

This study focuses on the experimental determination of saturation factors of a 20 MW synchronous generator at the Sapugaskanda Power Station in Sri Lanka. Field current and terminal voltage were determined with the AVR open-circuit test, within protection bounds, and subsequently analysed in order to construct the open circuit characteristic. The calculated saturation factors are presented and compared with traditional approaches. The findings provide updated saturation data for AVR and exciter system modelling, recognizing that generator parameters change over the operating life due to aging, wear, and operational stresses. With field tests to validate the generator's saturation characteristics, this research enhances the reliability of dynamic models used in power system stability analysis.

2. Literature review

2.1 Sapugaskanda Power Station

Sapugaskanda Power Station is one of the base load stations of Sri Lanka, which consists of two stations with a total capacity of 160 MW. Powered by heavy fuel, the plant provides lower operating costs than conventional diesel plants while allowing faster startup and shutdown features. This operational flexibility is particularly valuable in Sri Lanka's relatively small power system, which is prone to high power interruptions, abrupt load fluctuations, and stability problems. Sapugaskanda plays a critical role in system reliability under these circumstances. The plant is commissioned in 1984; the plant has been in continuous operation for over four decades. During this time, the generators have experienced extreme thermal, electrical, and mechanical stresses, leading to gradual aging. Because of this, the principal parameters of the synchronous machines may have deviated from their original design values, and hence periodic parameter estimation is necessary for meaningful modelling and performance analysis.

This research takes into account one of the 20 MW generation units in Sapugaskanda that possesses an AC excitation system. The generator uses a permanent magnet generator (PMG), mounted on the same shaft, to supply power to the AVR, which regulates the excitation. In this research, the open-circuit saturation test was performed with the AVR in manual mode to determine new generator saturation factors. An image of the generator during the test is provided in Figure 1.

Figure 2 – 20 MW Generator in Sapugaskanda Power Station

3. Methodology

Synchronous generator and excitation system modelling has been a long-standing cornerstone of power system stability studies. International standards such as IEEE Std 421.5-2016 [1], IEEE Std 1110-2002 [2], and IEEE Std 115-2009 [3] have provided comprehensive excitation system modelling guidelines, per-unit normalization, and generator testing. These documents collectively establish how open-circuit saturation characteristics are to be measured and saturation factors defined for application in simulation models. They are based on faithful representation of generator field current vs terminal voltage characteristics, since these significantly affect excitation control response and system stability under disturbance conditions.

Excitation system models, in particular the IEEE Type AC models, are derived from saturation factors that come from no-load tests in which a measure of the air-gap line to open-circuit saturation curve difference is made [4]. The calculation of the factors at the 1.0 pu and 1.2 pu levels of voltage has been made an industry standard for the purpose of representing generator magnetic nonlinearity [5]. Previous committee reports and studies have emphasized that generator aging, thermal effects, and material degradation can alter these saturation parameters over time, and this justifies the need for continuous validation [6,7]. Some previous studies also emphasized field voltage and field current base consistency, since they are direct inputs to AVR and exciter models [8].

Other than standards, previous research has also demonstrated the application of these principles to real power plants. For example, in a study [9] Experimental research was conducted on hydro-generator open-circuit testing to estimate magnetic saturation and used the results to enhance AVR models for stability studies. Similarly, in the study [10] field tests were conducted on a thermal power station generator to determine saturation curves and compare excitation model parameters with IEEE standards. These studies confirmed that empirical measures of open-circuit tests are needed to bridge the gap between theoretical models and the real machine behaviour. Most recently, [11] presented a comparative study of generator saturation factor estimation on different excitation systems, showing that field tests provide more accurate data for inclusion in modern stability programs than the use of factory data only.

According to these studies, this present research focuses on the identification of generator saturation factors of a 20 MW synchronous generator at Sapugaskanda Power Station, Sri Lanka. As opposed to other works that primarily tested new or hydro machines, this study targets an aged thermal unit that has been in commission since 1984. The test was run with the AVR in manual mode so that the field current could be altered progressively while recording corresponding terminal voltages within set overvoltage and undervoltage margins. The measurements were obtained using a Hioki power analyser. For each excitation step, only the steady-state RMS terminal voltage and the corresponding field current were used in the analysis, as these quantities are required to construct the generator open-circuit characteristic. The recorded data were processed in Excel to obtain the open-circuit characteristic curve and determine the saturation factors. The air-gap line was drawn, and the 1.0 pu and 1.2 pu voltage saturation factors were calculated according to [1].

The significance of this work is that it aids in supplying the present-day parameters of the generator for modelling. Since the machine has undergone considerable aging over decades of service, its magnetic characteristics have shifted from original design conditions. Experimentally obtained saturation factors thus provide realistic inputs to exciter and AVR models for stability simulations. Furthermore, this study demonstrates the usage of the IEEE-recommended approach in a Sri Lankan thermal power plant's industrial-sized generator, thereby providing a helpful guideline for future parameter estimation studies in that setting.

4. Generator Saturation Curve

Accurate synchronous generator modelling requires a correct representation of magnetic saturation effects. The conventional approach to defining and establishing generator saturation factors is explained in IEEE Std 421.5-2016 by using the open-circuit characteristic test. The method is based on comparing the actual open-circuit test curve of the machine with an idealized straight-line extension, or air-gap line, representing the unsaturated magnetic condition of the generator. The difference between the two curves is a measure of the magnetic saturation, which is more pronounced at higher levels of excitation.

Figure 2 in the IEEE standard illustrates the open-circuit characteristic and air-gap line where the actual generator voltage begins to leave the linear region as the field current rises.

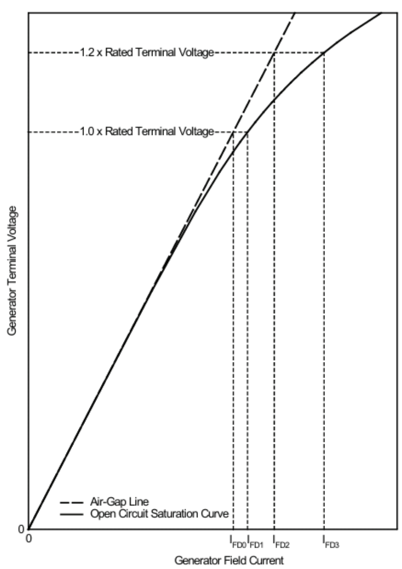

Figure 3 – Generator Open-Circuit Saturation Characteristic from IEEE standard [1]

To quantify this effect, the standard defines two saturation factors at two operating points: 1.0 pu and 1.2 pu of rated terminal voltage.

The equations are as follows.

$$S\ (1.0\ pu) = (I_{FD1} - I_{FD0})/I_{FD0}$$

$$S\ (1.2\ pu) = (I_{FD3} - I_{FD2})/I_{FD2} \quad ...(1)$$

Where I_{FD0} and I_{FD1} are the field currents at 1.0 pu and 1.2 pu terminal voltages on the air-gap line and I_{FD2} and I_{FD3} are the field currents at 1.0 pu and 1.2 pu terminal voltages on the open-circuit characteristic.

In the conducted study, the method was applied to a 20 MW synchronous generator in the Sapugaskanda Power Plant of Sri Lanka. The AVR was put on manual mode in order to allow the field current to be altered slowly by the operator. For operational safety, the test was carried out within the AVR protection limits; approximately 0.8 pu on the undervoltage side and 1.2 pu on the overvoltage side. These limits defined the safe area for the open-circuit characteristic test and avoided subjecting the generator to abnormal stresses.

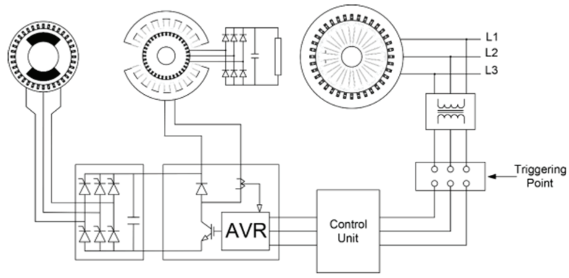

Figure 4 – Schematic diagram of generator and triggering point

The test was conducted at the Sapugaskanda control room under a planned shutdown, with the generator on open circuit as shown in Figures 4, 5 and 6. Under these conditions, the AVR setpoints were adjusted manually to regulate the excitation, and the terminal voltages and field currents thus produced were measured using a Hioki data acquisition system. These were then processed using Excel to graph both the open-circuit characteristic and the air-gap line. The saturation factors at 1.0 pu and 1.2 pu were then calculated from these in accordance with the IEEE standard.

Figure 5 – Test conducted at the Power Station

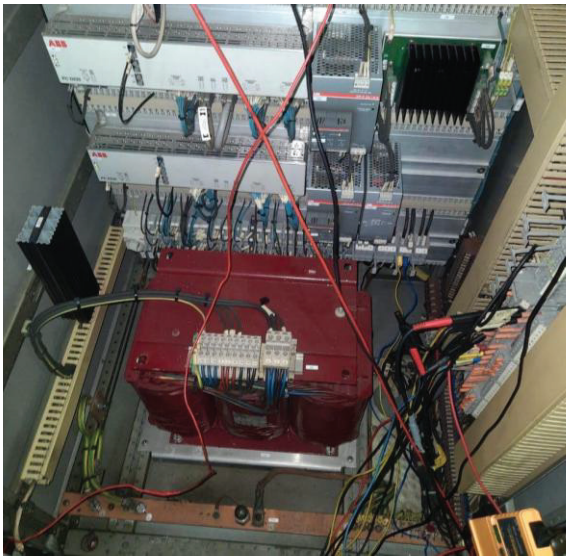

Figure 6 – Data collection using Hioki Machine connected to AVR Output

5. Results and Discussion

5.1 Results

The measured results of terminal voltage vs field current are shown in Figure 8.

The open-circuit characteristic curve is the nonlinear relationship between field current and terminal voltage. The curve has roughly a linear rise in terminal voltage with field current to begin with, corresponding to the unsaturated part of the magnetic core. With an increase in excitation current, however, the curve begins to depart from linearity and flattens out progressively. This indicates that the machine is reaching its saturation region, where the field current increase causes only a slight terminal voltage increase. This is highlighted in Figure 8, which was drawn from the data set as shown in Figure 7.

According to IEEE Std. 421.5–2016, the saturation factor is obtained by comparing the measured open-circuit characteristic with the linear air-gap line drawn through the low-excitation region. In Fig. 8, the linear region is identified where the measured curve follows this air-gap line, while the saturated region begins where the curve departs from it at higher excitation levels. The intersections used for saturation-factor calculation are taken at the specified voltage levels on the extended air-gap line and the measured open-circuit characteristic.

Name	Offline_GebV_0.7puTo1.2PU_OVtripped					
File	F:\AMTE - I&C\SPS\Parameter testing 2022_Gen9\Processed\Offline 0.7pu to 1.2pu.(					
Starttime of export	1.33071E+17	Tuesday, September 24, 2024	42:46.0			
Endtime of export	1.33071E+17	Tuesday, September 24, 2024	47:08.0			
Time Stamp	GCB	FieldCurrent (A)	FieldVoltage(V)	rFrequency(Hz)	Speed(rpm)	VoltageAvg(kV)
1.33071E+17	0	0.781273842	10.5478	49.75102	429.578552	8.022455
1.33071E+17	0	0.781273842	10.5478	49.75102	429.578552	8.022455
1.33071E+17	0	0.781273842	10.5478	49.7561836	429.578552	8.024419
1.33071E+17	0	0.781273842	10.5478	49.7613525	429.578552	8.024419
1.33071E+17	0	0.781273842	10.5478	49.7613525	429.578552	8.024419
1.33071E+17	0	0.781273842	10.5478	49.7657928	429.578552	8.026705
1.33071E+17	0	0.781273842	10.5478	49.7702332	429.578552	8.026705
1.33071E+17	0	0.781273842	10.5478	49.7702332	429.578552	8.026705
1.33071E+17	0	0.7843257	10.5478	49.77472	429.578552	8.028253
1.33071E+17	0	0.7843257	10.5478	49.7792	429.578552	8.028253
1.33071E+17	0	0.781273842	10.5478	49.7806473	429.578552	8.028253
1.33071E+17	0	0.781273842	10.5478	49.7806473	429.578552	8.028253
1.33071E+17	0	0.781273842	10.5478	49.7806473	429.578552	8.028253
1.33071E+17	0	0.781273842	10.5478	49.7849121	429.578552	8.029838
1.33071E+17	0	0.781273842	10.5478	49.7849121	429.578552	8.029838
1.33071E+17	0	0.781273842	10.5478	49.7849121	429.578552	8.029838
1.33071E+17	0	0.778221965	10.5478	49.79007	429.578552	8.030664

Figure 7 – Data set collected using Hioki Machine

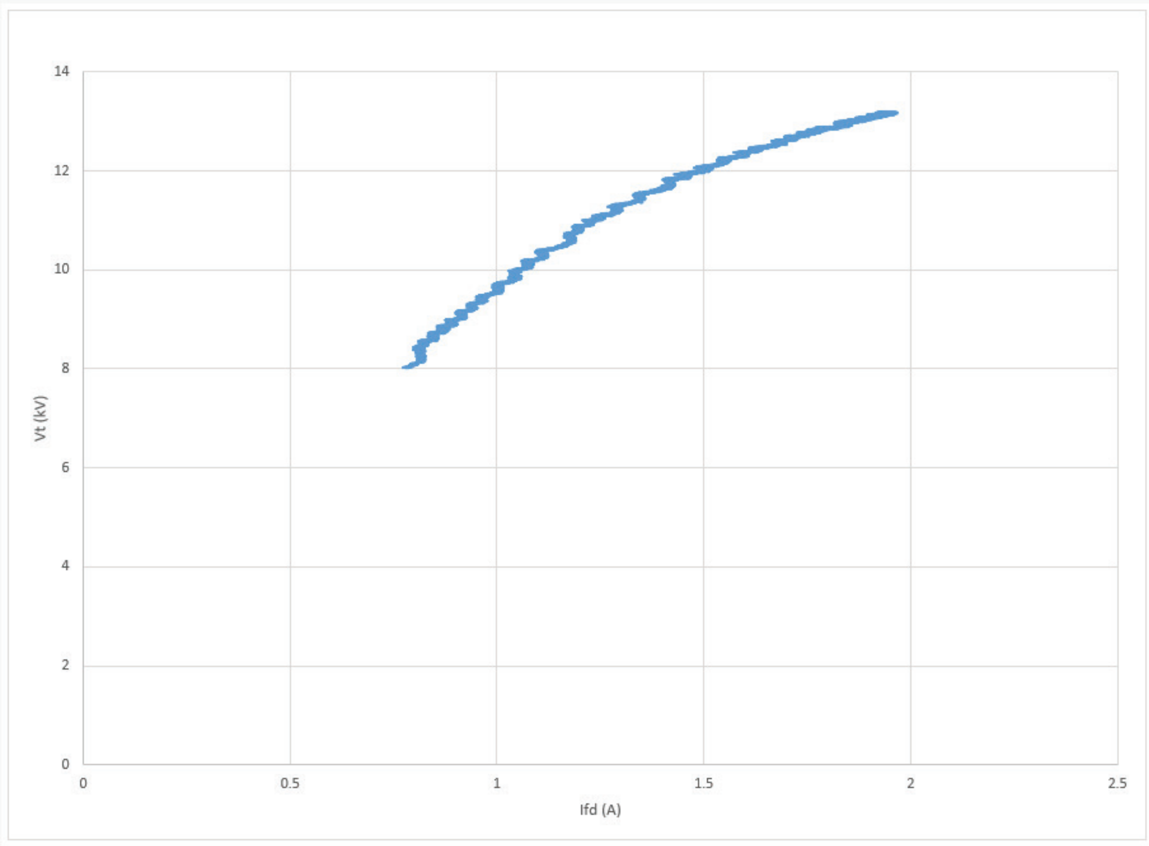

Figure 8 – Open-Circuit Saturation Test Curve obtained from measurements

5.2 Discussion

The open-circuit curve of the test result was also modified to comply with the suggested methodology by IEEE Std. 421.5–2016. The generator was subjected to the test in the experiment with an overvoltage protection limit of AVR at 13.2 kV (1.2 pu) and an undervoltage protection limit of AVR at 8.8 kV (0.8 pu). These limits guaranteed that measured data was within the safe operation range of the machine and yet picked up the nonlinear magnetic response of the synchronous generator. The dataset which was obtained, was then transferred to Excel for heavy processing and analysis.

To evaluate the saturation characteristics, the no-load saturation characteristic was plotted graphically in terms of measured terminal voltage as a function of field current. A trend line of a straight nature was graphed from this curve along the bottom, unsaturated portion of the curve, or the air-gap line as shown in figure 9. The air-gap line is utilized as a baseline line to obtain the level of magnetic saturation. The actual open-circuit characteristic curve, as it becomes nonlinear for higher field currents, shows the true performance of the generator core under increased excitation.

There were required intersection points of the air-gap line with the no-load saturation curve and were determined for both the rated terminal voltage (1.0 pu) and the overvoltage level (1.2 pu), as shown in Figure 9. Field current values at the subsequent points were read off directly from the plotted graph. At 1.0 pu terminal voltage, the field current of the air-gap line (I_{FD0}) was 1.051 A, and the actual saturation curve field current (I_{FD1}) was 1.246 A. Similarly, at the 1.2 pu voltage, the air-gap line field current (I_{FD2}) was 1.26 A, and the actual saturation curve field current associated with it (I_{FD3}) was 2.04 A.

Using the obtained values from the plotted graph the saturation factors were calculated according to the standard definition as given in equation (1). The saturation factor is precisely the relative variation between actual excitation current at saturation and ideal excitation current estimated from the linear air-gap line.

For the rated condition (1.0 pu), the saturation factor calculated from equation (1) was:

$$S\,(1.0\text{ pu}) = (I_{FD1} - I_{FD0})/I_{FD0}$$

$$S\,(1.0\text{ pu}) = (1.246 - 1.051)/1.051 = \underline{0.1855}$$

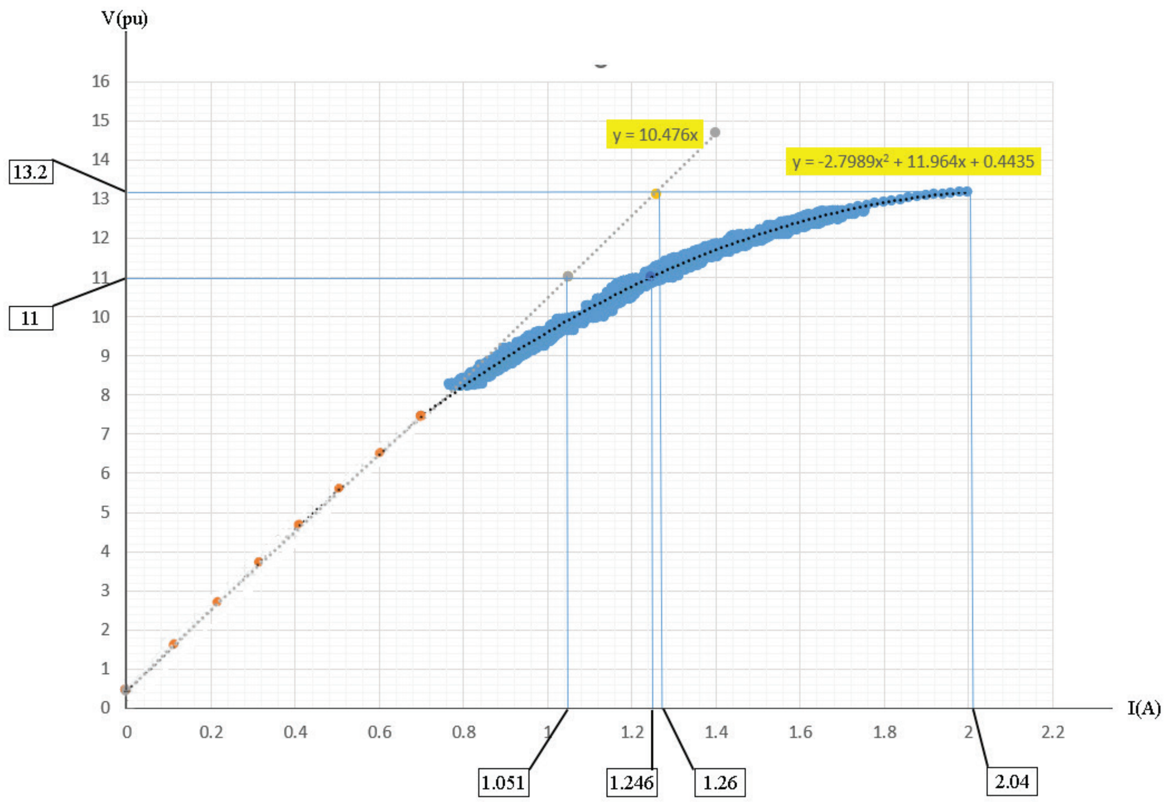

Figure 9 – Refined Open-Circuit Saturation Test Curve

For the overvoltage condition (1.2 pu), the saturation factor calculated from equation (1) was:

S (1.0 pu) = (I_{FD3} – I_{FD2})/I_{FD2}

S (1.0 pu) = (2.04 – 1.26)/1.26 = <u>0.6190</u>

These tests clearly show how the generator's magnetic core exhibits strong nonlinearity with an increase in the level of excitation. At 1.0 pu voltage, the machine is close to its linear region with a quite small value of the saturation factor equal to 0.1855, demonstrating that the additional requirement of excitation is moderate. But at 1.2 pu, the saturation factor increases drastically to 0.6190, demonstrating the wide effect of core saturation at higher levels of excitation. This agrees with the prediction from theory that magnetic materials exhibit much deviations from linearity as they approach their saturation flux density.

The utilitarian value of this analysis is that it can be applied to AVR and exciter control models. Since the AVR must compensate for nonlinearities in the generator response, accurate determination of saturation factors ensures system simulations are representative of actual behaviour. The range of values for the overvoltage and rated conditions further emphasizes the need for taking saturation into account at more than one operating point, rather than relying on a single measurement.

Overall, the smoothed curve and subsequent determination of saturation factors provide a clear and quantitative representation of the generator's magnetic behaviour. The results confirm that the check synchronous generator exhibits the expected saturation characteristics, wherein the saturation factor increases significantly at high voltage levels. Such computed values are a critical input to dynamic modelling and enhance the reliability of simulation-based research on excitation systems in generators.

6. Application in Excitation System Modelling

With the saturation factors determined experimentally, they can be employed as direct inputs to IEEE-recommended models of excitation systems. In particular, the AC rotating exciter with non-controlled rectifier model shown in Figure 9 has a saturation function block $S_E(V_E)$ that requires saturation factors at 1.0 pu and 1.2 pu as its input in order to simulate the generator nonlinearities accurately. The values of 0.1855 at 1.0 pu and

0.6190 at 1.2 pu obtained in previous results were inserted in this block to emulate the actual magnetic behaviour of the generator.

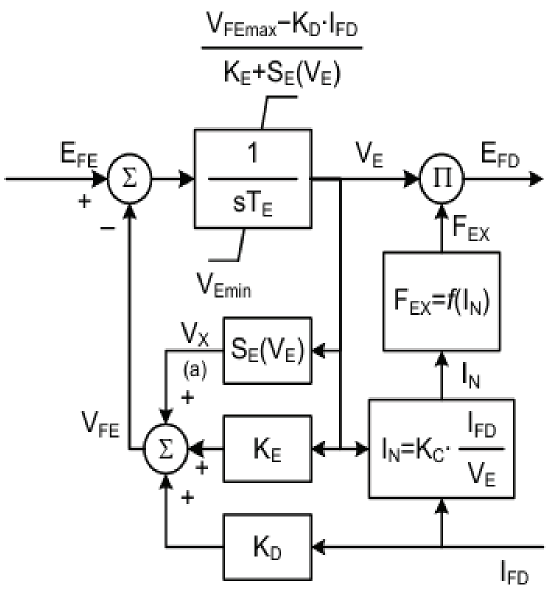

Figure 10 – AC rotating exciter with non-controlled rectifier model [1]

To validate the updated parameters, a dynamic simulation of the excitation system was carried out in MATLAB/Simulink using the IEEE-based AVR/exciter model with the experimentally determined saturation factors. A small disturbance was applied to E_{REF} within the excitation range where saturation begins to influence the generator response, and the corresponding terminal-voltage response was measured during the open-circuit test. The same disturbance was applied in simulation, and Figure 11 compares the two responses. The lower damping observed in the measured response is attributed to practical nonlinearities and modelling uncertainties not fully captured in the simulation.

The comparison reflects satisfactory agreement of the simulation with the actual machine behaviour, which confirms that the experimentally determined saturation factors accurately represent the current state of the Sapugaskanda unit. Significant deviation would have indicated that the saturation function in the model was not adequately parameterized. The close approximation therefore validates both the experimental method employed in this study as well as the IEEE model capacity to describe generator nonlinearities when given proper values of saturation factors. This finding is significantly important as the machine has been in operation for over four decades, where its parameters have strayed from original factory settings.

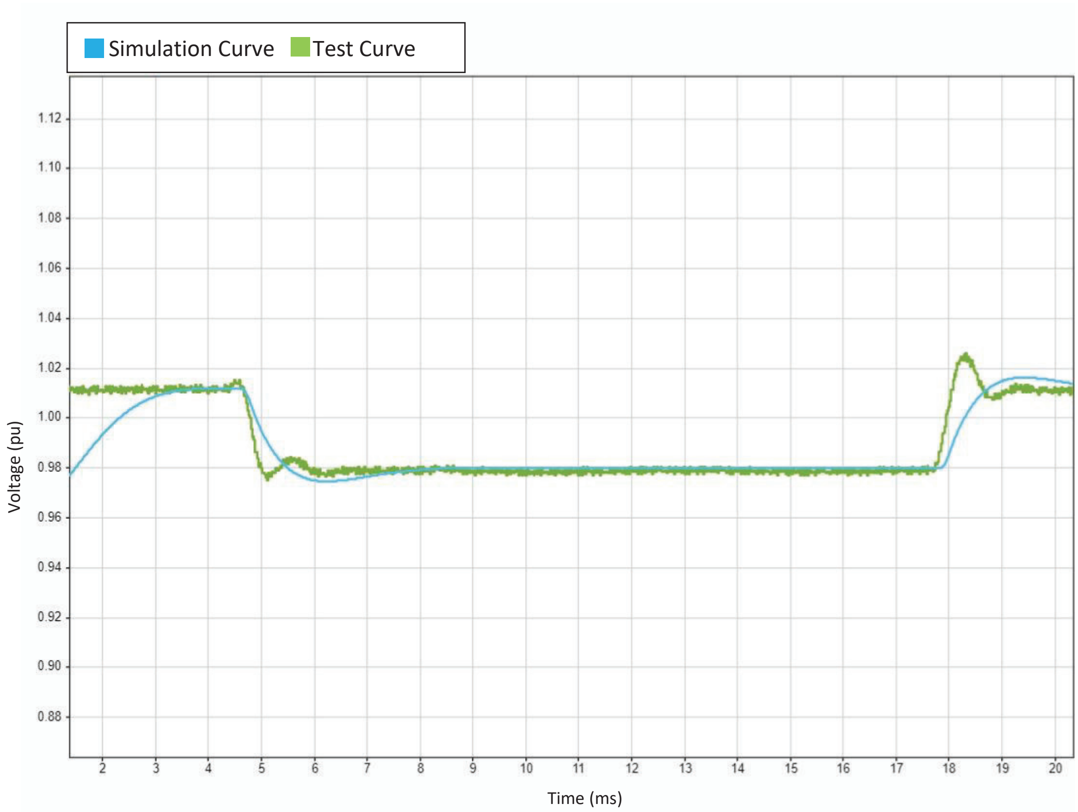

Figure 11 – Comparison of Simulation and Test Curve

7. Conclusion

This work experimentally determined the synchronous generator saturation factors of 20 MW thermal unit of Sapugaskanda Power Station, Sri Lanka, under open-circuit tests with AVR in manual mode. Open-circuit saturation characteristic and corresponding air-gap line were found based on IEEE Std. 421.5–2016 by measuring terminal voltage–field current pairs with high-precision meters while excitation was controlled carefully within AVR protection limits. Out of these, 1.0 pu and 1.2 pu operating point saturation factors were calculated as 0.1855 and 0.6190, respectively, indicating a substantial increase in magnetic nonlinearity with rising excitation levels. These not only confirm theoretical expectations but also emphasize the practical significance of the incorporation of saturation effects explicitly into generator and AVR models. Notably, this study demonstrates the importance of routine re-estimation of these parameters in aging utility equipment, since long-term exposure to thermal, electrical, and mechanical loading can modify the magnetic properties relative to the original factory design data. For Sapugaskanda unit, commissioned in 1984, the research provides a welcome update to its modelling parameters, ensuring stability computation and exciter tests adhere to today's machine action rather than past assumptions. Beyond local application, the findings are evidence that open-circuit testing, when conducted under carefully controlled conditions, still represents a good and practical method for field verification of generator saturation characteristics on industrial-scale units. The calculated factors also show the inadequacy of sole reliance on linear approximations or on default values in dynamic models, as such a strategy may result in very large errors in AVR performance prediction, transient response, and overall system stability margins. Through the presentation of both methodology and findings on an actual plant machine, this study adds not just empirical evidence but also a reproducible model for other utilities to follow, especially in areas where old thermal fleets remain contributing to grid reliability. In the future, the findings indicate a larger programme of routine testing and parameter updating across the national generation fleet accompanied by comparative studies evaluating the influence of aging on magnetic saturation on diverse machine types and excitation systems. These exercises will support improved power system modelling reliability, increase operator trust in stability calculations, and ultimately facilitate more robust and reliable grid operation in Sri Lanka and elsewhere.

References

1. IEEE, *IEEE Recommended Practice for Excitation System Models for Power System Stability Studies*, IEEE Std 421.5-2016, 2016.

2. IEEE, *IEEE Recommended Practice for Synchronous Generator Modeling Practices and Applications in Power System Stability Analyses*, IEEE Std 1110-2002, 2002.

3. IEEE, *IEEE Guide: Test Procedures for Synchronous Machines*, IEEE Std 115-2009, 2009.

4. Kundur, P., *Power System Stability and Control*. New York, NY, USA: McGraw-Hill, 1994.

5. IEEE Committee Report, "Proposed definitions of per unit quantities and base for synchronous machines," *IEEE Trans. Power Apparatus and Systems*, Vol. PAS-92, No. 6, pp. 1916–1920, Nov./Dec.1973.

6. IEEE Power and Energy Society, *IEEE Recommended Practice for Excitation System Models for Power System Stability Studies*, IEEE Std 421.5-2016,Apr.2016.

7. Anderson, P. M., and A. A. Fouad, *Power System Control and Stability*, 2nd ed. Piscataway, NJ, USA:IEEE,Press/Wiley,2003.

8. P. Kundur, N. J. Balu, and M. G. Lauby, *Power System Stability and Control*, EPRI Power System Engineering Series. New York, NY, USA: McGraw-Hill,1994.

9. IEEE Working Group on Computer Modelling of Excitation Systems, "Excitation system models for power system stability studies," *IEEE Trans. Power Apparatus and Systems*, Vol. PAS-100, No. 2, pp. 494–509, Feb. 1981.

10. IEEE Committee Report, "Synchronous machine parameters and their measurement," *IEEE Trans. Power Apparatus and Systems*, Vol. PAS-92, No. 2, pp.455–465,Mar./Apr.1973.

11. Semlyen, A., and Medina, A., "Calculation of saturation characteristics for synchronous machines from test data," *IEEE Trans. Energy Conversion*, Vol. 5, No. 2, pp. 293–299, Jun. 1990.

12. González-Morán, J., Conde, A., García-Gracia, M., and Lorenzo, F., "Experimental determination of synchronous machine saturation characteristics for AVR modeling," *IEEE Trans. Energy Conversion*, Vol. 24, No. 2, pp. 388–395, 2009.

13. Hongesombut, K., and Pothisarn, C., "Generator parameter estimation through open-circuit testing in thermal power plants," *Electric Power Systems Research*, Vol. 97, pp. 142–150, 2013.

14. Silva, L. M., Ramos, R., and Martins, N., "Comparative analysis of generator saturation factor estimation methods for excitation system modeling," *IET Generation, Transmission & Distribution*, Vol. 11, No. 12, pp. 3110–3118, 2017.