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Investigation of Frequency Reduction Behavior on Three Phase Synchronous Generator And Transformer

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Abstract:

Using three-phase synchronous generators basic units in power plants, the main source for feeding alternating current. The electromagnetic force (e.m.f) given by these generators depend mainly on the number of pairs of poles in the Member excitement and speed of rotation cycles of the generator. Since the number of pairs of electrodes are part of the structural arrangement of generator will not change due to overload, but it will be the adoption of frequency only on the speed with which revolves where the generator. The power transformers are the heart's main power plants and power transmission and delivery to the consumer and based on the work of the converted electric depends on electromagnetic induction, so the performance of work directly related to the frequency in which they operate. It is through this research will be identified on the behavior of each of the born Synchronous and transferred electrical in the case of low frequency. This is done checks of laboratory and compared to examine the system simulation through the language of MATLAB has been done to change the frequency and noting the effect on each of the power factor, efficiency and organization of voltages for each of the converted and born Synchronous and show results in the form of charts.

Keywords*:* **Frequency Reduction, Under Frequency, Synchronous Generator, Transformer.**

1. Introduction:

Three phase synchronous generators are the primary source of all electrical energy we consume. These machines are the largest energy converters in the world; they convert the mechanical energy in to the electrical energy in power ranging up to 1500 MW [1].

A synchronous generator is one in which alternating current flows in the armature winding, and dc excitation is supplied to the field winding. The armature winding is almost invariably on the stator and is usually a three-phase winding. The field winding is on the rotor. A single synchronous generator supplying power to an impedance load acts as a voltage source whose frequency is determined by the speed of its mechanical drive (or prime mover). The amplitude of the generated voltage is proportional to the frequency and the field current. The current and power factor is then determined by the generator field excitation and the impedance of the generator and loads [2].

The permissible change of the frequency is ±0.01%.Two years ago, and due to severe circumstances of electrical power generation and distribution in Iraq ,the frequency was forced to be reduced to about 47.5Hz(5% reduction)due to generation shortage and high load demand. Any part of power system will begin to deteriorate if there is an excess load over available generation. The prime movers and their associated generators begin to slow down as they attempt to carry the excess load .Tie lines to other parts of the system, or to other power systems across the generation shortage, attempt to supply the excess load. This combination of events can cause the tie lines to open from overload or the various parts of the system to separate due to power swing resulting instability. The result may be one or more electrically isolated islands, in which load may exceed the available generation [3].

The under frequency behavior (UFB) is an old phenomenon so many researchers stand for this problem to discuss its effect on the generating plants some of these researchers are:

1. BUTLER O.D. and SWENSON P.G., [4], in 1955: In his paper some tests are made for many generating stations. These tests stated that at 11.33%reduction in frequency, some auxiliaries of the generating stations were out of service and the motors of the feeders slow down directly about 7.1% from its rated speed. At 7% reduction in frequency, the speed of high pressure feed pumps reduced about 8%. Also the tests clarified that the coal mills would become critical items below 6.66% reduction in frequency and the high pressure boiler feed pumps would become critical below that rate of frequency reduction.
2. BERDY J. and BROWN P.G., [3], In 1974: presented a paper that discusses the protection of steam turbine generators during abnormal frequency conditions. The major concern has been considered with regard to possible damage of the steam turbine due to prolonged operation at reduced frequency during a severe overload conditions. They tried to declare that the turbine and generator are limited to a degree of off frequency operation.
3. The Institute of Electrical and Electronics Engineers (IEEE), 2003, [5],produced a guide for abnormal frequency protection for power generating plants, this guide covered relay applications for the protection of generating plant equipments from damages caused by operating at abnormal frequencies.
4. Mats Larsson, 2005, [6], studied the frequency stability of the electrical power system. Frequency stability, which was studied in this paper, denotes the ability of a power system to operate with the (average) system frequency within normal operating limits. Failure to do so may cause damage to generation and/or load side equipment, and power plants are most often equipped with under frequency protection relays that disconnect the plant if the network frequency is lower than say 47 Hz for a 50 Hz system or 56-57 Hz for a 60 Hz system.

2. Theoretical analyses.

2.1 Three Phase Synchronous Generator

The generator type in this paper is a salient pole generator, a salient-pole rotor has larger air gap in the region between the poles than in the region just above the poles.

The synchronous reactance is split in to two components, the direct axis (d-axis) synchronous reactance (X_d), and the quadrature-axis(q-axis) synchronous reactance (X_q). In the same manner the armature current is also resolved into two components, direct component ($\overline{I_d}$) and the quadrature component ($\overline{I_q}$). The direct component ($\overline{I_d}$) is produces a field lags the internal voltage ($\overline{E_a}$) by 90°. The quadrature component ($\overline{I_q}$) produces a field in phase with ($\overline{E_a}$). So that the terminal voltage of the generator will be:

$$\overline{V_a}=\overline{E_a}+\overline{E_d}+\overline{E_q}-\overline{I_a}*R_a \tag{1}$$

Also ($\overline{E_d}$) and ($\overline{E_q}$) can be expressed in terms of(X_d) and(X_q) as below

$$\overline{E_d}=-j\overline{I_d}*X_d \tag{2}$$

$$\overline{E_q}=-j\overline{I_q}*X_q \tag{3}$$

($\overline{I_d}$) and ($\overline{I_q}$) can be expressed in terms of (I_a) as

$$\overline{I_d} = I_a \sin(\delta + \theta) \angle\delta - 90 \quad (4)$$

$$\overline{I_q} = I_a \cos(\delta + \theta) \angle\delta \quad (5)$$

Where (Ia) is the r. m. s. value of the armature current. When the armature resistance is neglected thus

$$I_q = \frac{Va \sin\delta}{Xq} \quad (6)$$

$$I_d = \frac{Ea - Va \cos\delta}{Xd} \quad . \quad (7)$$

The output power can now be computed as

$$P_o = 3 \operatorname{Re}[\overline{V_a}\,\overline{I_a}] = 3 \operatorname{Re}\left[\overline{V_a}\,(\overline{I_d} + \overline{I_q})\right]$$
$$= 3\ V_a\,[I_d \sin\delta + I_q \cos\delta] \quad (8)$$

Phasor diagram of a salient pole synchronous generator with a neglible armature resistance and lagging power factor is shown in **Fig.** (1) [7].
Finally the generator voltage regulation is obtained as

$$V.R_{\%} = \frac{\overline{E_a} - \overline{V_a}}{\overline{V_a}} * 100\% \quad (9)$$

2.2 Three Phase Transformer.

The primary windings of three phase transformer have been connected to the generator output terminals, and the three types of loads have been connected to the transformer secondary side. The circuit represents the transformer load test is shown in **Fig.** (2).

The transformer efficiency and voltage regulation must be evaluated, the transformer must be referred to one of its sides (the secondary winding for example) and all voltages, currents, and impedances must be referred to the secondary side. So that the approximate equivalent circuit of the transformer referred to secondary side will be as in **Fig.** (3).

Under this assumption all the transformer formulae has been rearranged to be suitable with the secondary side [8].

Transformer percentage voltage regulation is $VR_{\%} = \frac{V_P' - V_s}{V_s} * 100\%$ (10)

Where

$$V_P' = V_s + I_s(R_{eqs} + jX_{eqs}) \quad (11)$$

V_P' =Is the primary voltage referred to secondary winding in volt.

R_{eqs} is the transformer resistance referred to secondary side in (Ω)

X_{eqs}= the transformer reactance referred to secondary side in (Ω)

The transformer copper losses is

$$P_{cu} = I_s^2 R_{eqs} \tag{12}$$

The transformer core losses is

$$P_{co} = \frac{V_P'^2}{R_c} \tag{13}$$

2.3 Under Frequency Phenomenon.

In normal load variations and operating conditions on an interconnected power system, the balance between the mechanical input power to the generating unit prime mover and the electrical power output of the generating unit is maintained by the combined regulating reserve of all units. However, when this condition of equilibrium is upset by a major disturbance such as the loss of a major tie-line, the loss of a large generating station, or a sudden impact of a major overload, a severe generation/load imbalance may occur. This would result in a fast frequency decline [9].

Power station auxiliaries, in thermal and other power stations, can only function effectively within a limited frequency range. The heavy loss of generation causes frequency to fall below its nominal level by 2 cycles or more, power station auxiliaries can rip out, causing power stations to be shut down and leading to the collapse of entire power systems [10].

2.3.1 Effect of frequency reduction on the synchronous generator.

Calculations indicate that generator efficiency changes only slightly with frequency, a 10% reduction in frequency increases generator efficiency only about 0.1% [4].

Generator cooling fans will be operating at lower speed which will reduce the hydrogen or air flow in the cooling system and may affect the thermal limits of the machine depending on the duration of the emergency.

Calculations indicate that a 10% reduction in frequency, with steam conditions and flow kept constant, reduces the turbine capability about 0.9%. Continued operation at 10% reduced frequency; with maximum steam flow may result in a vibration in the wheels due to inadequate margins for axial and tangential vibration. It should be emphasized that due to the limited range of turbine governor speed changers difficulty in synchronizing additional generators to the bus will generally occur when the system frequency is 2 to 5% below normal (the generator frequency must equal to the system frequency in the synchronizing of a generator with the system) [5].

Fig. (4a) shows the effect on maximum output of a change in pump speed corresponding to a drop in frequency from 50 to 44 cycles. For the 10% drop in speed, the maximum turbine output drops 0.7% [5].And **Fig.** (4b) stated that at 47Hz the active power will reduced to 95% from the rated value, while in the range (49.5-50.5) Hz the active power will be at its rated value. The test demonstrated that the main power reduction was at rate of 2% per 0.1 Hz reduction in frequency [11].

2.3.2 Steam turbine behavior in under frequency operation.

A steam turbine is comprised of many stages of turbine buckets of various lengths and designs, each of which has its own characteristic natural frequencies (which is the frequency of any rotating part of the generating plant). Turbines are carefully designed so that the bucket resonance and stimulus frequencies at rated speed are sufficiently far apart to avoid vibration and excess stress. However, departure from rated speed will bring the stimulus frequencies closer to one or more of the bucket natural frequencies with resulting higher vibratory stresses. **Fig.** (5) illustrates the phenomena involved in off-frequency; it shows the bucket vibration stress amplitude for a composite of the stages of the turbine as a function of running frequency where A, B and C are the stress levels. Note that below level A, the vibration stress amplitude is low enough that the buckets can run indefinitely without any damage. Operation at stress level B would product a failure because of the vibration and at a still higher stress level C, failure would occur too. It is clear that as the turbine moves off frequency, the amplitude increases and some damage is accumulated [3].

The resonant blade vibration cannot be observed by the operator or detected by any instruments. This resonant blade vibration is discernible only after it has caused a blade or blades to fail [12].

2.3.3 Effect of frequency reduction on Power plant.

Similar to that in steam station the hydro stations are also influenced by the frequency reduction. This type of stations can operate at normal rated generation with 8% reduction and 12.5% reduction in frequency .the governor in this station was placed on a hand control and the speed reduced about 12.5% from the rated speed. An induction motors will slow down with a decrease in frequency, therefore, as the induction motors which was driving the main unit exciter reduced its speed; the main unit exciter output voltage would be reduced. [12].

3. Experimental Part.

The experimental test rig is shown in the **Fig.** (6), this test rig is consist of a DC motor as a prime mover for the generator, three phase synchronous generator, three phase transformer and three phase loads (resistive, capacitive and inductive).The same work is repeated using MATLAB SIMULINK program to simulate the experimental test rig work and to verify the results, the model represents the generator and transformer simulated circuit is shown in **Fig.** (7).

The generator experimental work is subdivided in to

1. Tests for generator parameters estimation.
2. Load test.
3. Temperature test.
4. Vibration test.

The transformer tests needed in this work are almost the same as the generator load test, various transformer losses estimation and tests needed for parameters estimation.

The generator and transformer tests, in general, will be made by the experimental test rig starting from rated frequency (50Hz), and then the frequency has been rebuked by 0.5Hz step on each step until reaching 47Hz.

The generator parameters estimation tests are

a. DC test to evaluate the generator armature and field resistances ($\mathrm{R_{ag}}$) and ($\mathrm{R_{fg}}$), also the same think is done to the DC motor.
b. Slip test for synchronous generator to evaluate $\mathrm{X_d}$ and $\mathrm{X_q}$.
c. Sudden Short Circuit Test to evaluate the transient and sub transient reactance ($\mathrm{X'_d}$ and $\mathrm{X''_d}$). The extraction of three phase short circuit current waveform is achieved by an interface circuit between the generator output current and NI-PCI-6023E data acquisition card(DAQ) made by National Instrumentation Company.

In the load test, many parameters are estimated, such as the generator internal voltage ($\overline{\mathrm{E}}_\mathrm{a}$), the load (torque) angle (δ), the generator efficiency (η), and voltage regulation. This test is performed with the three types of loads, unity, leading and lagging power factor loads at reduced frequency. The final results are shown in **Figs**. (8, 9 ,10) respectively.

The temperature test is performed using the procedure explained in reference [13] the final temperature results are shown in **Fig.** (11). Finally the results of the vibration test are in **Figs**. (12 ,13).

The transformer load test results are shown in **Figs**. (14, 15,16) respectively.

4. Conclusions.

The under frequency phenomenon in the electrical generating plant has many effects on the generators and the auxiliary equipments which are equipped with the generator. These effects are:

1. Possibility of damage of the turbine due to prolonged operation at reduced frequency during a severe overload conditions, this is clear in **Fig.** (5) and vibration tests.
2. Generators, transformers and turbines all have operational frequency limitations. Turbine capabilities are generally more restrictive than those of generators and transformers. Operation of generators at low frequencies can result in overheating, due to reduced ventilation as it is clear in temperature test.
3. At 47Hz the active power will reduced to 95% from the rated value, while in the range (49.5-50.5) Hz the active power will be at its rated value. The test demonstrated that the main power reduction was at rate of 2% per 0.1 Hz reduction in frequency as it is cleared in **Fig.** (4b).
4. Tests in this research indicate that the generator and transformer efficiency is increased at all the types of loads, except in the case of the transformer leading power factor the efficiency of the transformer is reduced at the frequency reduction .
5. The voltage regulation of the generator becomes better as the frequency decreased to 6% in the cases of unity (12.1%) and lagging power factors (8.75% for 0.9 lagging pf and 10.58% for 0.8 lagging pf). In the case of leading power factor the generator absolute value of the voltage regulation increases as the frequency of the generator decreases (12.2% for 0.9 leading pf and 10% for 0.8 leading pf).
6. The power factor of the generator load will increase in the frequency reduction behavior at 6% reduction for lagging power factor loads, (0.88% for 0.9 lagging pf and 1.2 for lagging pf), while the power factor will decrease at leading power factor loads (3.1% for 0.9 leading pf and 1.5 for 0.8 leading pf) in the same frequency reduction rate.
7. From the vibration test it obvious that at a particular reduced frequency value (generator natural frequency) the vibration value will jump to increase to a certain value and the after further reduction the vibration value will be back to the normal value. In the vibration test it is clear that the vibration increased in the frequency range (48.5-49.5) in **Figs**. (12,13).

5. References.

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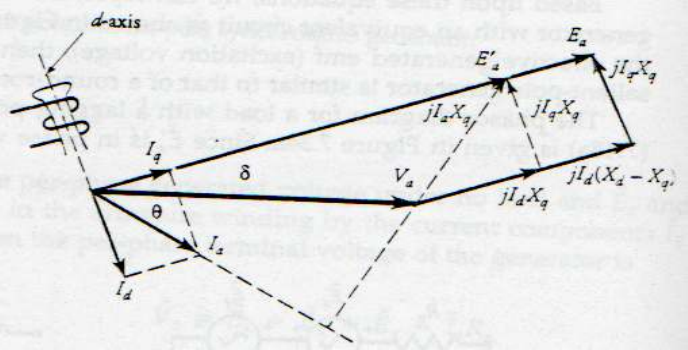


Figure (1): Phasor diagram of a salient pole synchronous generator.

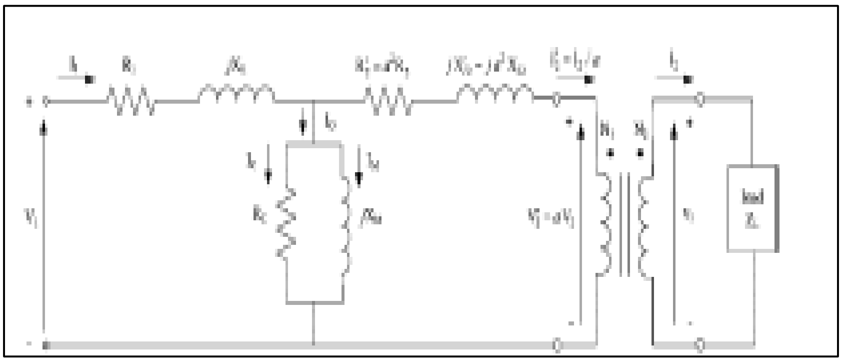


Figure (2): transformer load test Circuit diagram.

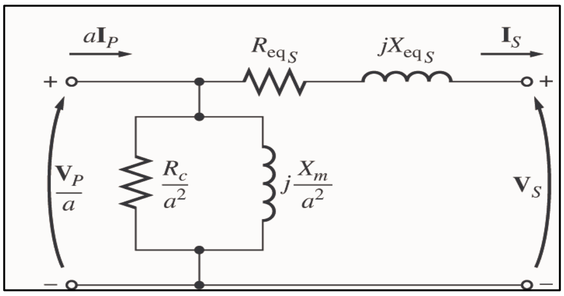
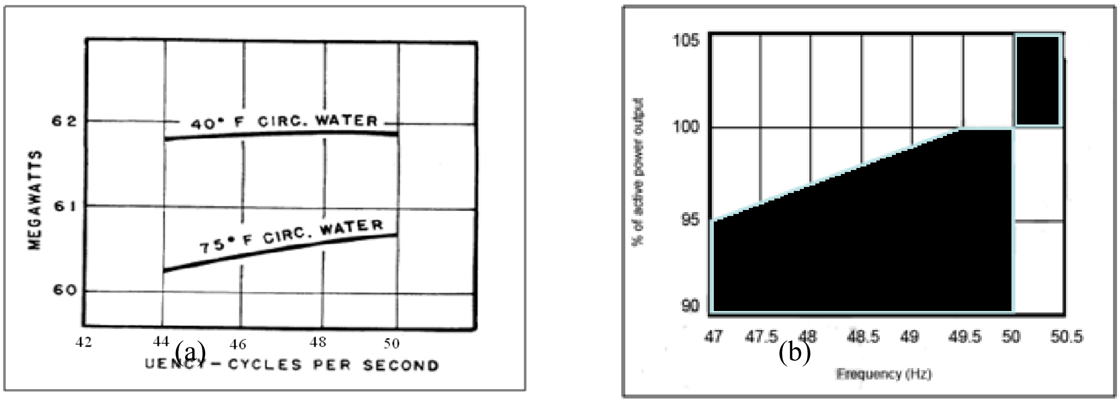


Figure (3): transformer equivalent circuit referred to secondary side.



(a)

(b)

Figure (4): effect of frequency reduction on generator output.

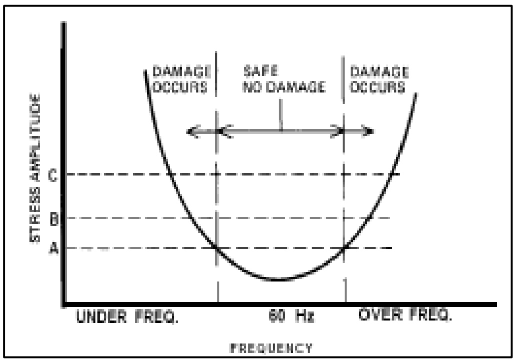


Figure (5): increase in stress amplitude with off frequency operation.

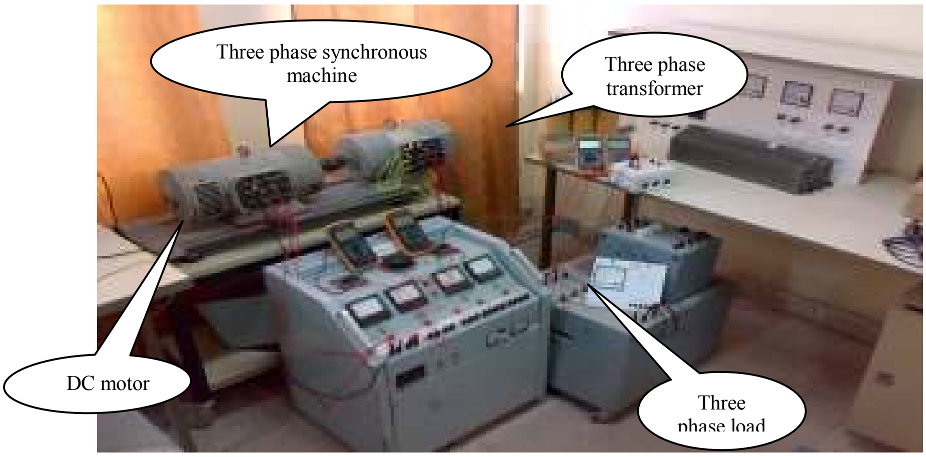


Figure (6): experimental test rig circuit diagrams.

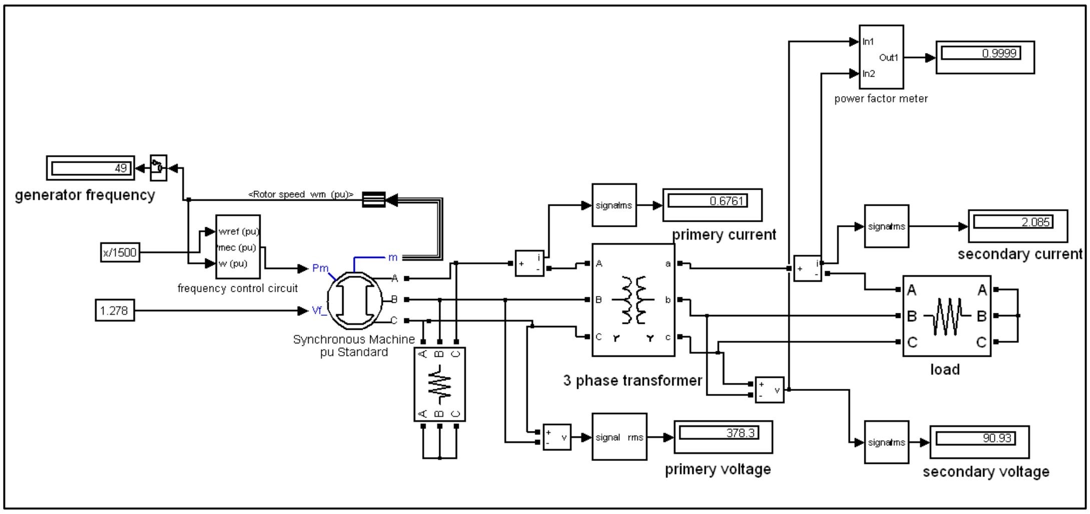
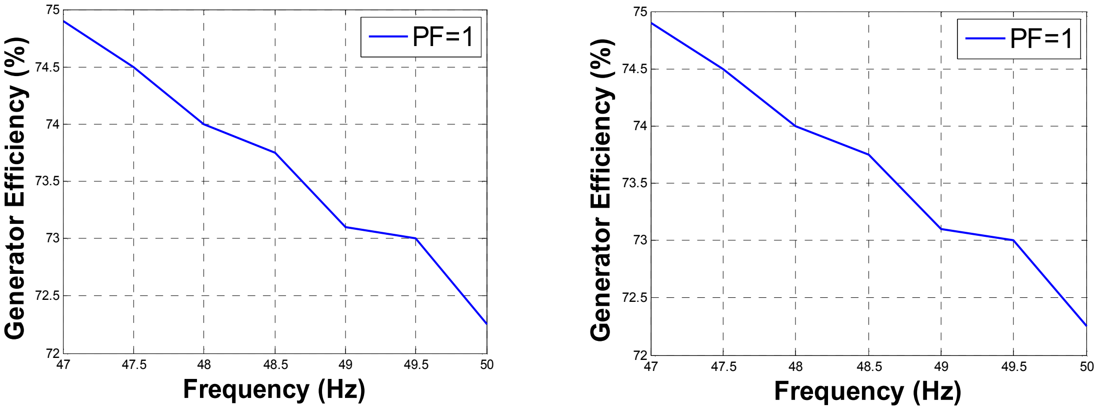
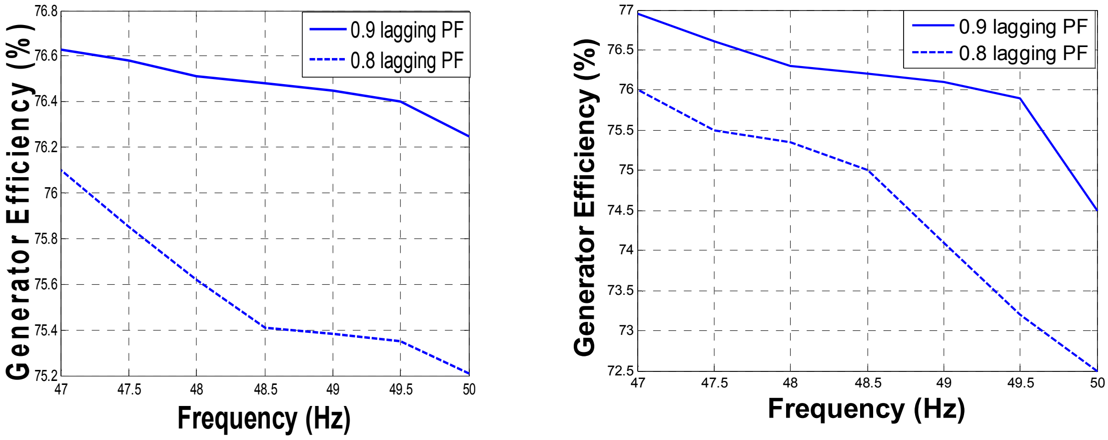


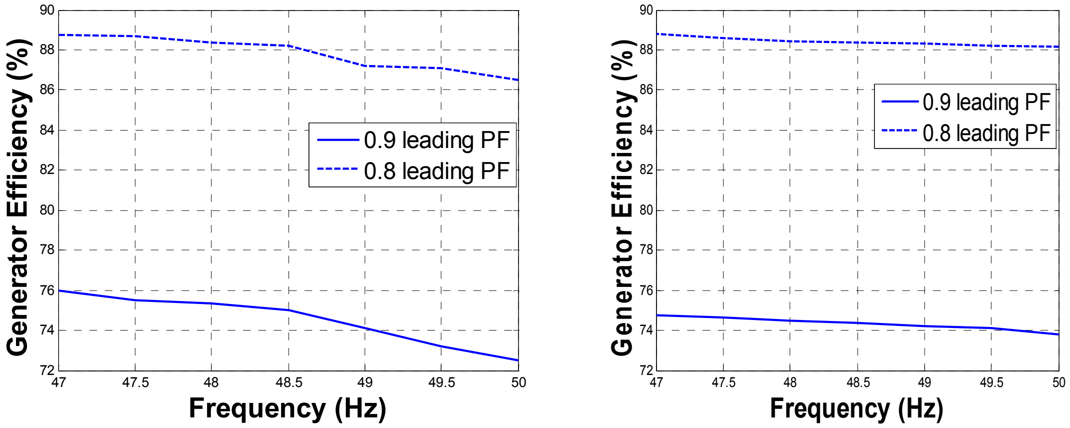
Figure (7): MATLAB SIMULINK simulation for transformer and generator.



(a)Experimental (b) Simulated

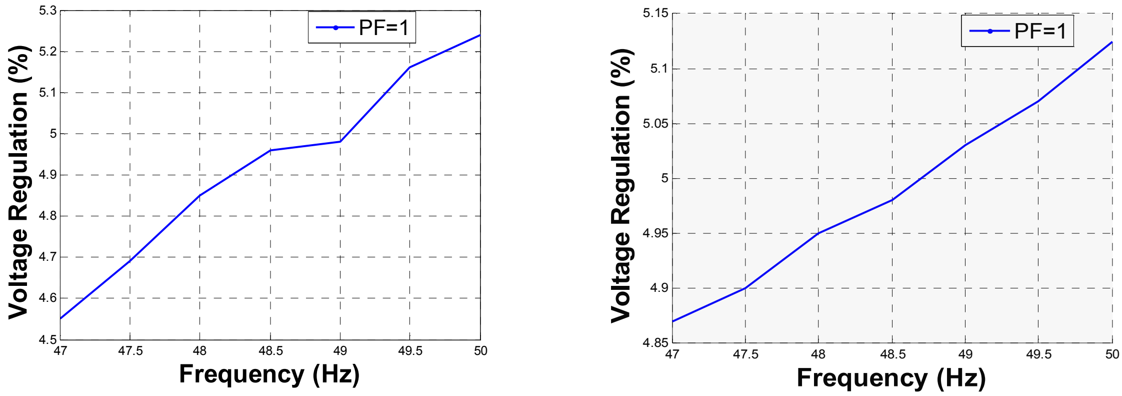


(c)Experimental (d) Simulated

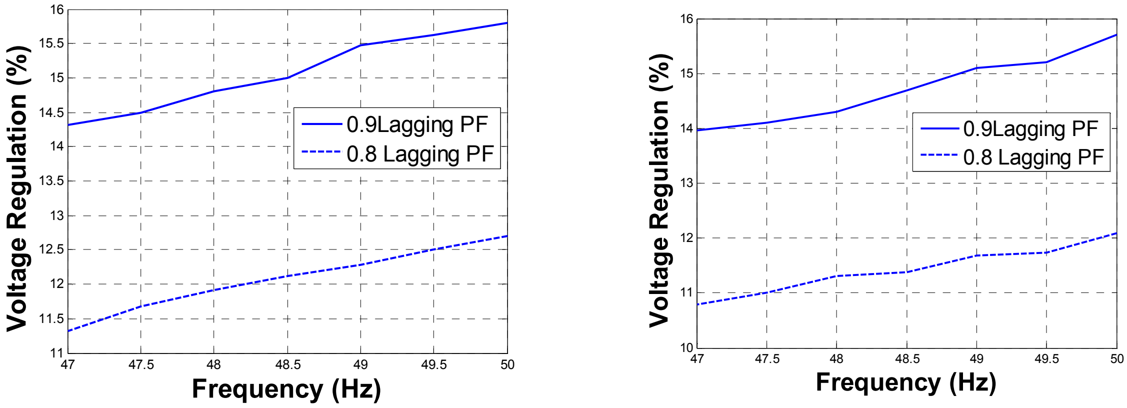


(e)Experimental (f) Simulated

Figure (8): variation of generator efficiency with frequency (a, c, e) experimental results, and (b, d, f) simulated results.



(a) Experimental (b) Simulated



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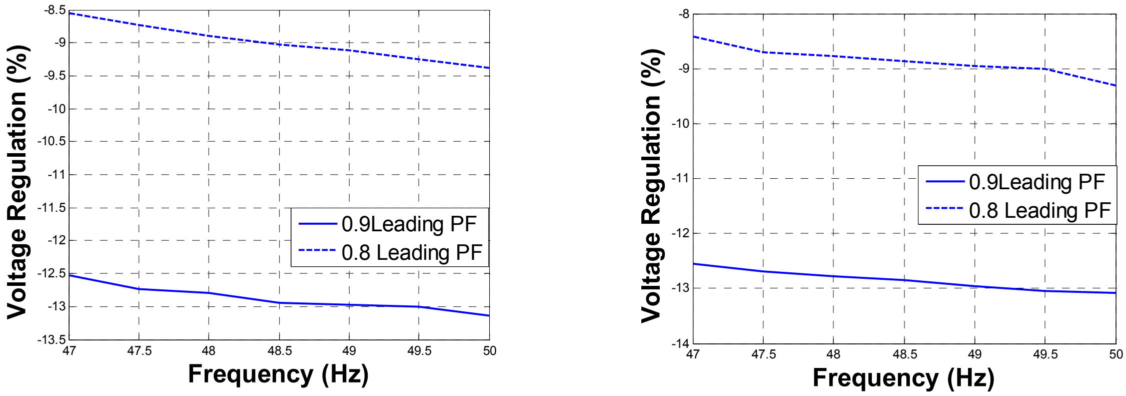
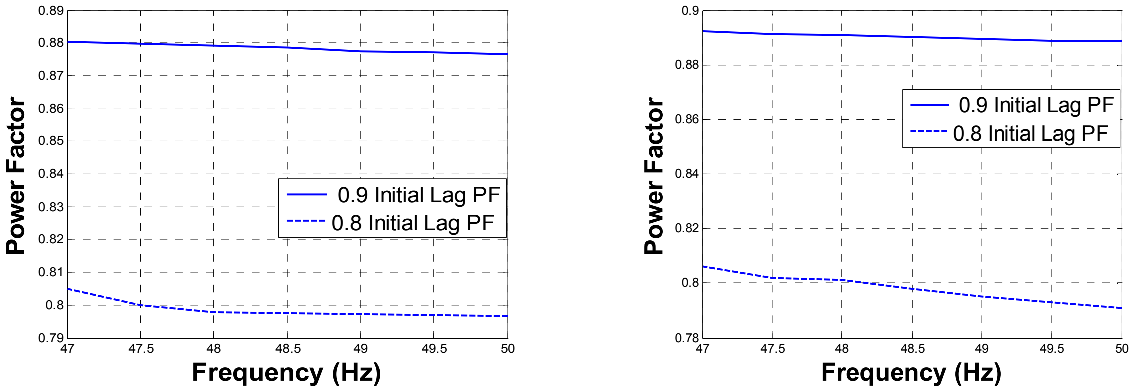
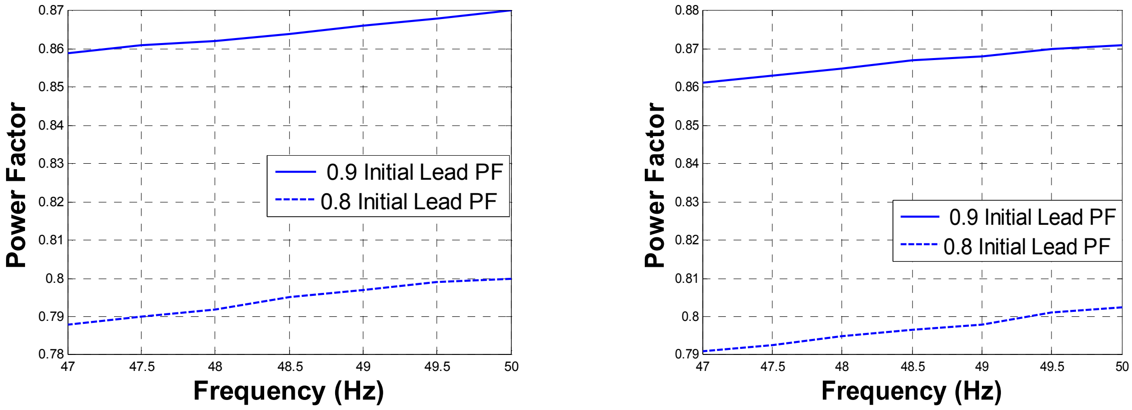


(e) Experimental (f) Simulated

Figure (9): variation of generator voltage regulation with frequency (a, c, e) experimental results, and (b, d, f) simulated results**.**



(a) Experimental (b) Simulated



(c) Experimental (d) Simulated

Figure (10): variation of generator load power factor with frequency at constant generator field current (a, c) experimental results, and (b, d) simulated results.

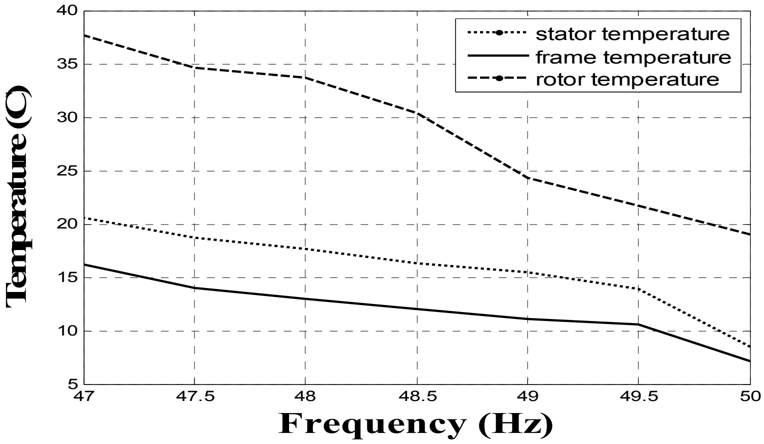
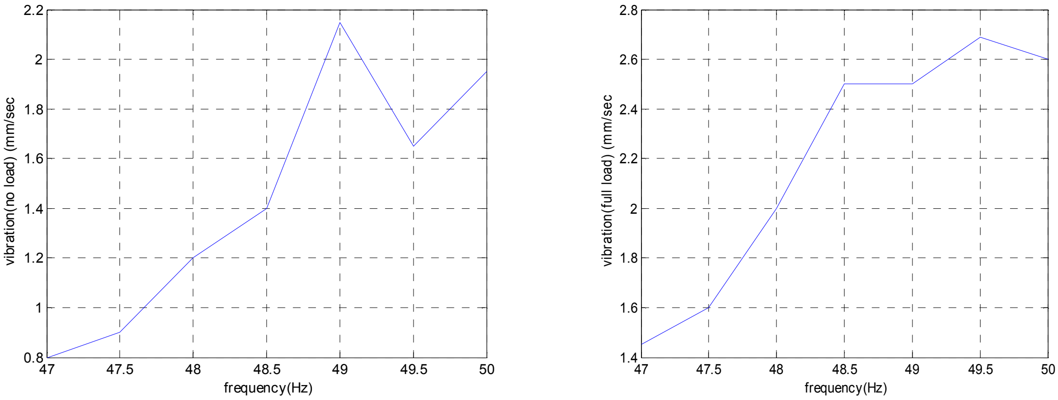


Figure (11): temperature test results.



(a) .

(b)

Figure (12): frequency verses vibration at no load (a) and at full load (b).

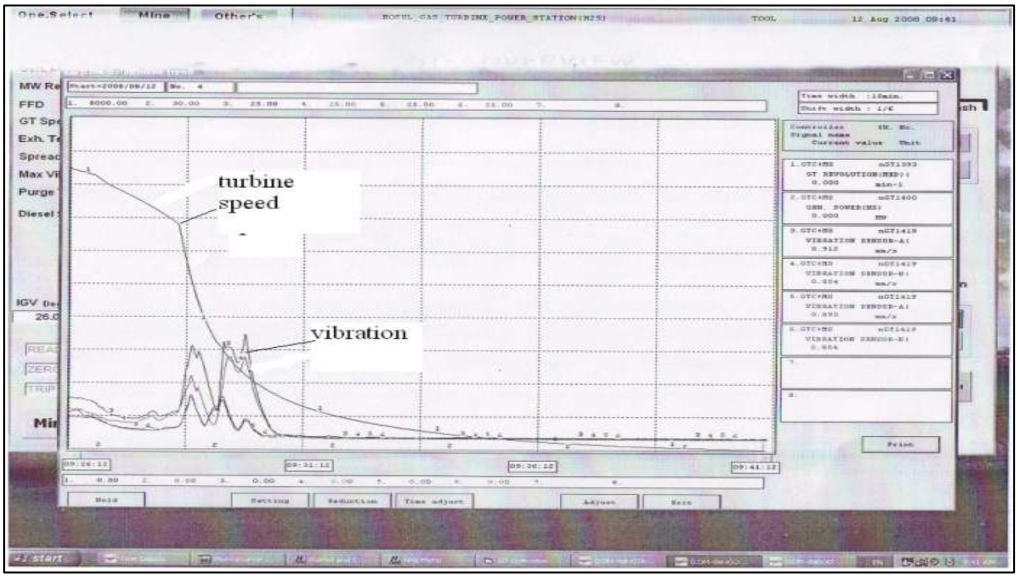
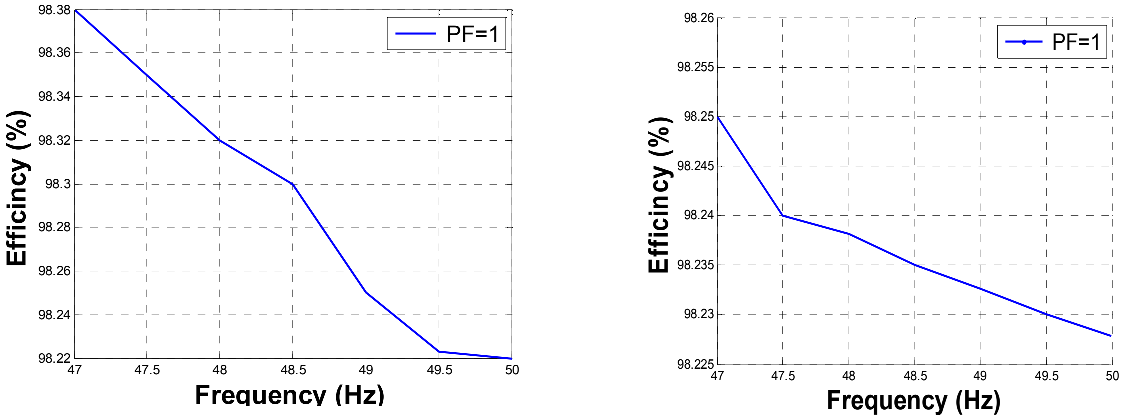
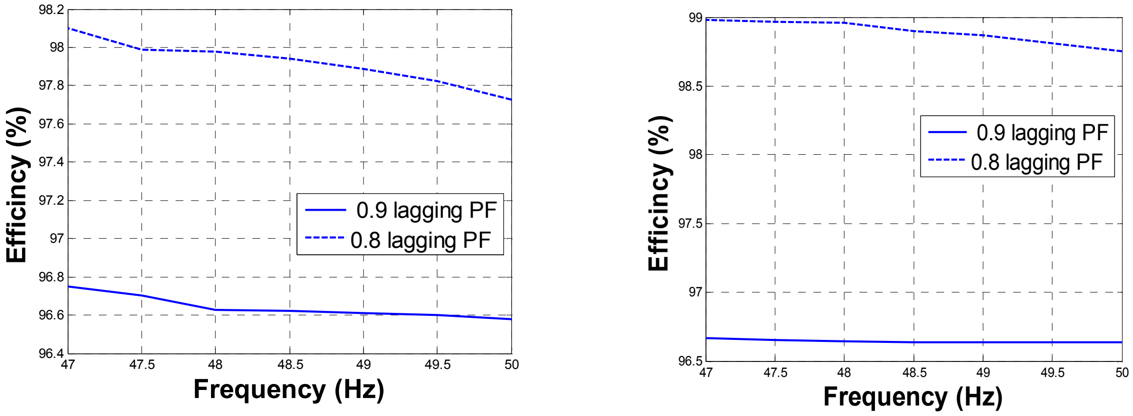


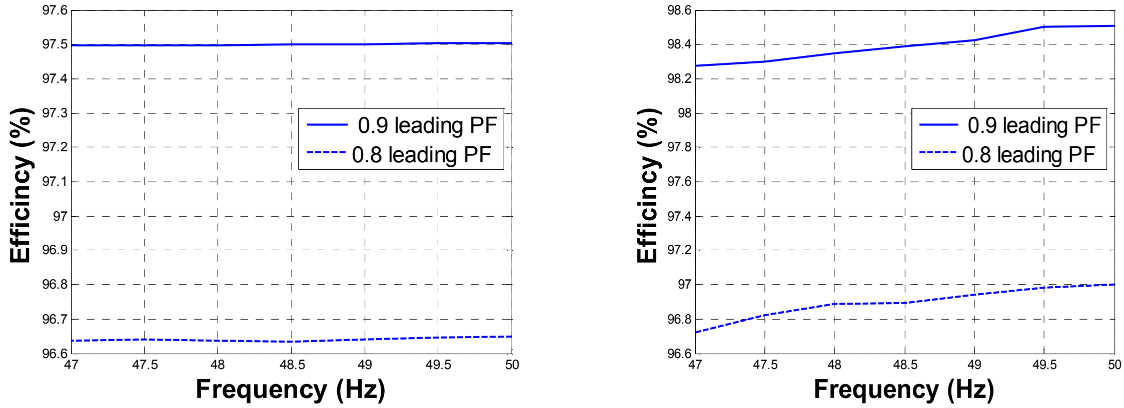
Figure (13): vibration results obtained from Mosul Gaseous Station.



(a) Experimental (b) Simulated

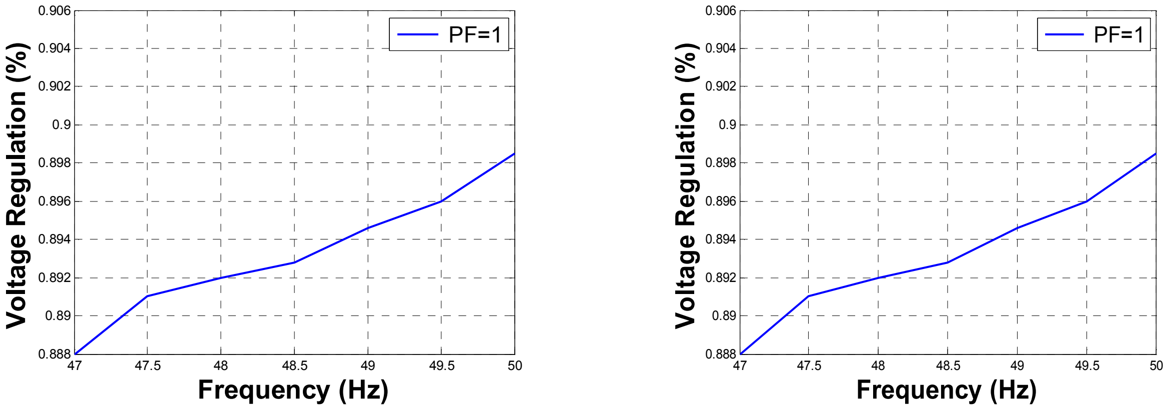


(c) Experimental (d) Simulated

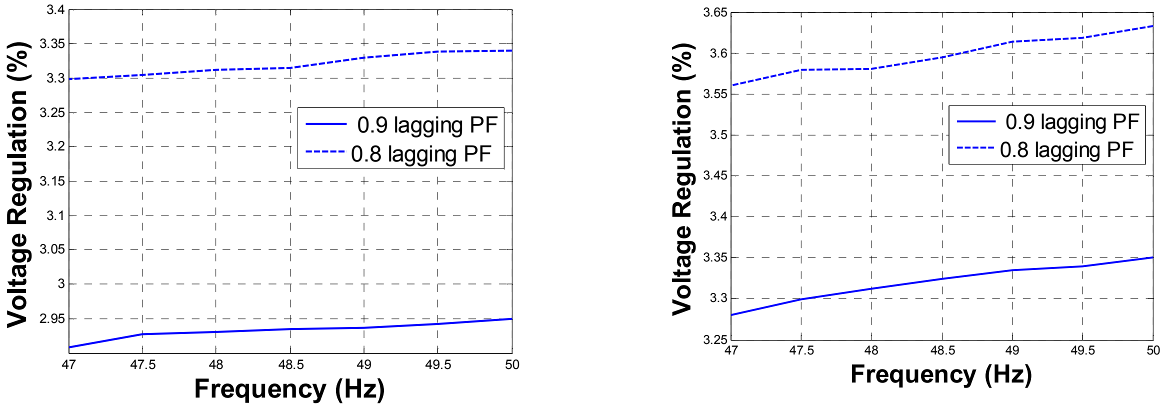


(e) Experimental (f) Simulated

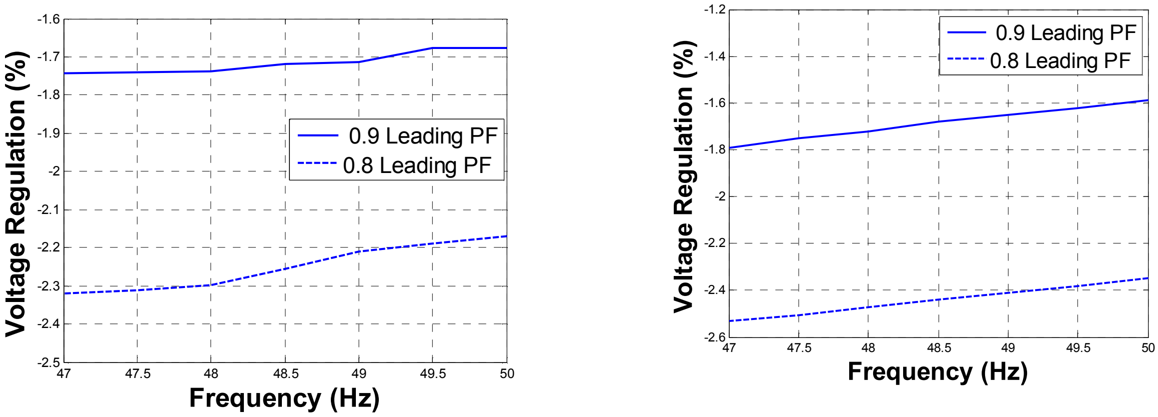
Figure (14): variation of generator efficiency with frequency (a, c, e) experimental results, and (b, d, f) simulated results.



(a) Experimental (b) Simulated

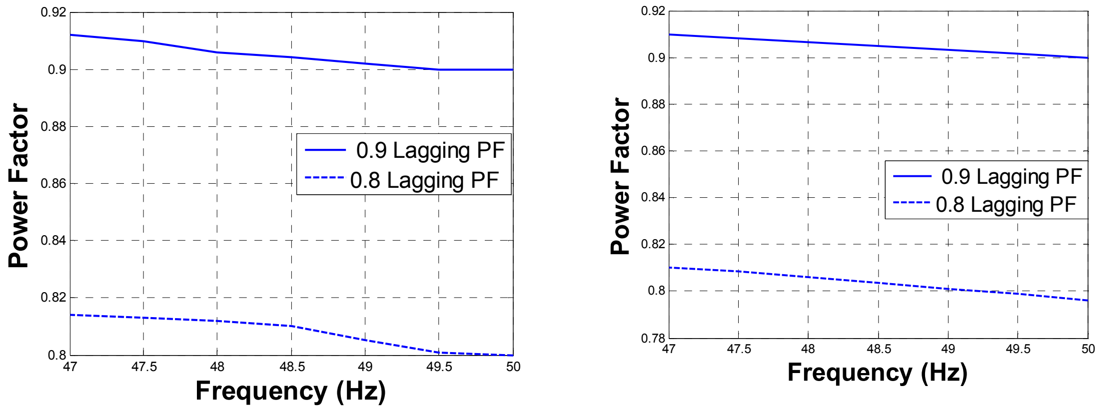


(c) Experimental (d) Simulated

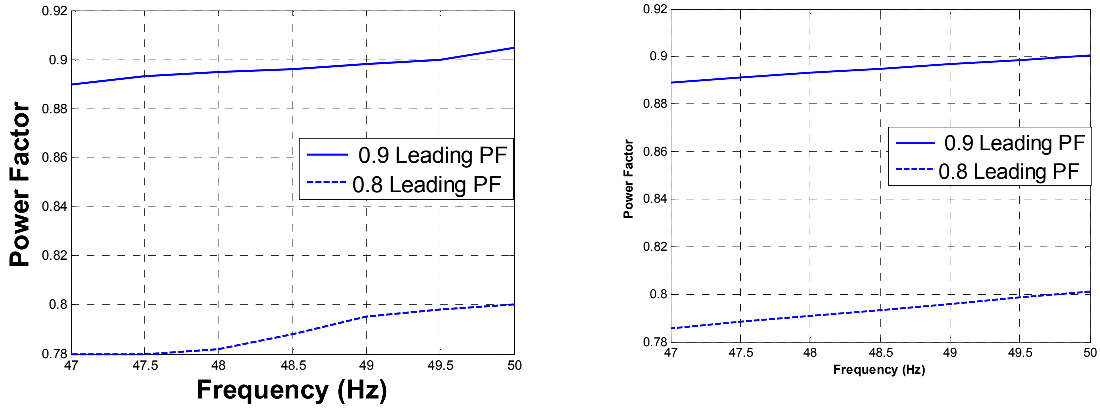


(e) Experimental (f) Simulated

Figure (15): variation of transformer voltage regulation with frequency (a, c, e) experimental results, and (b, d, f) simulated results.



(a) Experimental (b) Simulated



(c) Experimental (d) Simulated

Figure (16): variation of transformer load power factor with frequency (a, c) experimental results, and (b, d) simulated results.

اختبار تأثير انخفاض التردد على مولد تزامني ثلاثي الطور والمحولة الكهربائية

محمد حسن درويش

جامعة تكريت- كلية الهندسة

الخلاصة.

تستخدم المولدات التزامنية ثلاثية الطور كوحدات أساسية في محطات توليد الطاقة الكهربائية، وهي المصدر الرئيسي لتغذية جهد التيار المتناوب. وان تردد القوة الدافعة الكهربائية التي تعطيها هذه المولدات يعتمد بالأساس على عدد أزواج الأقطاب في عضو الإثارة وعلى سرعة الدوران التي يدور فيها المولد.وبما أن عدد أزواج الأقطاب هي من الجزء التركيبي للمولد فلن تتغير نتيجة الحمل الزائد وإنما سيكون اعتماد التردد فقط على السرعة التي يدور فيها المولد.أما المحولات الكهربائية فهي القلب الرئيسي في محطات توليد ونقل الطاقة الكهربائية وإيصالها إلى المستهلك.وان أساس عمل المحولة الكهربائية يعتمد على الحث الكهرومغناطسي لذا فان أداء عملها له علاقة مباشرة بالتردد الذي تعمل به.ومن خلال هذا البحث سيتم التعرف على سلوك كل من المولد ألتزامني والمحولة الكهربائية في حالة انخفاض التردد.ويتم ذلك بفحوصات مختبريه ومقارنتها بفحص بنظام المحاكاة من خلال برنامج بلغة ماتلاب وتم ذلك بتغيير التردد وملاحظة مدى تأثيره على كل من عامل القدرة والكفاءة وتنظيم الفولتية لكل من المحولة والمولد ألتزامني وإظهار النتائج على شكل مخططات.

الكلمات الدالة: انخفاض التردد ،التردد التحتي ، مولد تزامني ، المحولة الكهربائية.