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Design Modifications to Reduce a Brushless Exciter Response Time

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Abstract

As an alternative to converting a brushless exciter to static excitation in order to improve an exciter's response time, conversion of the existing conventional brushless exciter is possible. A high initial response (HIR) brushless excitation system has the ability to force its output to ceiling voltage in 0.1 second or less, which is a response time similar to a static excitation system. To achieve the required fast response time, various modifications to the existing exciter components are required, including the ac exciter stator, permanent magnet generator (PMG), and voltage regulator. This paper describes those required modifications and associated technical information. This paper presents a concept solution that decreases the response time of a brushless exciter in order to respond to grid disturbances via the excitation system, while minimizing modification of the existing excitation system configuration.

Keywords: Brushless exciter; static exciter; response ratio; conventional response time; high initial response; permanent magnet generator (PMG); ac exciter stator; ac exciter armature; IEEE model; voltage regulator; ceiling voltage; ceiling current; response time.

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1. Introduction

In planning and operating electric power systems, utilities have expressed the need to select from a wide range of excitation voltage response times, in which excitation systems are usually categorized to be either normal response or high initial response (HIR) [5]. This may also involve the selection of normal or high ceiling voltages. A brushless excitation system has the design flexibility to meet various response needs. How fast a brushless excitation system can respond depends upon the inductive nature of the exciter field and how quickly the exciter field can change magnetic flux. A conventional response brushless excitation system has limitations in the ability of the exciter to quickly change flux, and thus when forced to ceiling will have an exponential response under loaded conditions with a time constant typically around 0.5 second or so. A high initial response (HIR) brushless excitation system employs the combination of a higher voltage forcing capability to the exciter field and a lower inductance of the exciter field to allow fast flux changes within the exciter. When called on to force to ceiling voltage, the result is a linear response to ceiling which reaches ceiling in 0.1 second or less [3,5].

Compared to a conventional response brushless excitation system, an HIR brushless excitation system employs the following features to achieve the required fast response time:

- Allow faster changes in exciter flux by designing the exciter field with a lower inductance. This inductance is affected by design factors such as the number of turns, the size of the field pole conductors and the air gap between the field poles and the rotating armature.
- Design the complete magnetic path of the exciter stator (including the field poles and frame upon which they are mounted) to allow fast changes in flux while preventing them from inducing opposing circulating currents in the magnetic circuit.
- Force faster changes in exciter flux by employing a PMG with a higher voltage and current rating so to increase the exciter field voltage forcing capability from the voltage regulator.
- Employ an instantaneous exciter field current limiting function in the voltage regulator to limit forcing when exciter field ceiling current is reached.
- Employ feedback function in the voltage regulator for fast small-signal response as well as fast large-signal response.

While achieving fast response times similar to static excitation, an HIR brushless excitation system has certain advantages over a static system, particularly in a conversion from conventional response brushless excitation to an excitation system having HIR characteristics. These include:

- Less impact on plant design and footprint (no large power transformer, large rectifier banks, and associated bus-work is required).
- No brushes or collector rings with their associated maintenance and carbon dust.
- All excitation power derived from shaft rotation.
- No reduction in ceiling voltage during grid faults or depressed system voltage conditions, since all excitation power is derived from shaft rotation and none from any external voltage source.

2. Response of a Conventional Brushless Exciter

There are two principal means of providing field excitation to a synchronous generator [1]: static and brushless excitation. A potential source static excitation system draws ac power from the generator terminals or local power system via an excitation transformer. The excitation transformer, which must be designed for duty as a rectifier transformer, supplies ac power to a static thyristor assembly, which rectifies it and produces controlled dc power. The rectified dc power is connected via dc bus-work or cables to a set of stationary conductive carbon brushless and rotation slip rings, often called a “collector”, and transferred to the generator rotor field.

A brushless exciter has three basic parts (a permanent magnet generator, an ac exciter and a rectifier wheel). The field of a set of rotating permanent magnets is utilized for the primary source of excitation thereby eliminating the need for an external energy source. The rotating permanent magnet generator (PMG) field induces a voltage in the stationary armature windings, thereby eliminating the need for the brushes and current-collection devices at this point [1,9]. This permits feeding the relatively high-frequency (typically 420 Hz), 3-phase output of the PMG stator to the voltage regulator where it is rectified and controlled in magnitude. The dc output is then fed to the stationary ac exciter field winding where it induces a voltage in the rotor-mounted ac exciter armature winding. This ac output is rectified by wheel-mounted diodes on the rotor shaft, producing the exciter dc output voltage. The main excitation power is fed directly to the field winding in the generator rotor by short leads located in the center of the shaft or through leads which pass through two diametrical slots on the periphery of the exciter-to-generator coupling [2,8]. The major components of a typical brushless excitation system are shown in Figure 1.

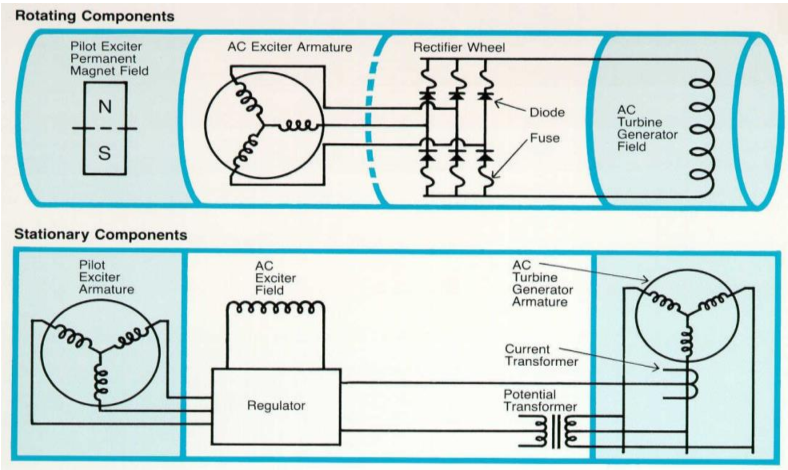

Figure 1: A typical Conventional Brushless Exciter Diagram

Any brushless exciter will have the following rating characteristics:

- Armature Current - the armature current is the maximum amperes which may be carried through the armature winding continuously without exceeding guaranteed temperature rise.
- Armature Voltage - the armature voltage is the maximum voltage which may be delivered continuously by the armature without exceeding the guaranteed temperature rise or producing excessive magnetic saturation.

- Field Current - the field current is the number of direct current amperes which must be circulated through the field winding in order to deliver rated voltage at rated armature current, power factor and speed.
- Field Voltage - the field voltage is the number of direct current volts required to circulate rated field current through the ac exciter field winding.
- Number of Phases - the number of phases is the number of separate circuits on the exciter armature.
- kVA Output - the kVA output is the product of armature current and armature voltage divided by 1000 (and also multiplied by 1.732 in the case of a 3-phase exciter.
- kW Output - the kW output is equal to kVA output multiplied by power factor. In other words, it is the real power delivered by the exciter feeding into the rectifier load.
- Power Factor - The power factor is a measure of how nearly the current and voltage are in phase with each other. It is set by the requirements of the rectifier circuit to which power is being delivered.
- Speed - The speed of the machine is defined as the number of revolutions per minute.
- Temperature Rise - The rated temperature rise is a function of the class of insulation used. This is a prime factor in setting the voltage and current ratings, since the flow of current in both the armature and field circuits is accompanied by a copper loss in the conductors, which varies as the square of the current.
- Frequency - This is the frequency of the ac exciter voltage before rectification.

The frequency of an ac exciter is a function of the number of poles and the speed. One complete cycle results from an armature coil traversing one pair of poles and then repeats itself. The frequency (f) in Hz is:

$$f = \frac{\#\,poles}{2} x \ \frac{rpm}{60} \ or \ \frac{\#\,poles\ x\ rpm}{120} = \frac{pxN}{120}$$

The range of frequencies most usually encountered in the ac exciter is between 120 and 420 Hz. Table 1 shows actual examples of brushless exciters, with rated speed in rpm, the corresponding to the number of ac exciter poles, and the resulting frequency.

Table 1: A.C Exciter poles, speed and armature frequency

No. of poles	*RPM*	*Frequency (Hz)*
8	3600	240
10	3600	300
12	3600	360
14	3600	420
8	1800	120
14	1800	210
16	1800	240
20	1800	300
24	1800	360

Depending on the specifier's preference, an exciter may vary in response ratio, ceiling voltage and response time. Per IEEE Std 421.1, excitation system nominal response or response ratio is the rate of increase of the excitation system output voltage determined from the excitation system voltage response curve, divided by the rated field voltage [1]. This rate, if maintained constant (curve ac in Figure 2), would develop the same voltage-time area as obtained from the response (curve ab) over the first half-second interval (unless a different time interval is specified). Most exciter designs are based on a minimum response ratio of 0.5 with the exciter loaded into the generator field.

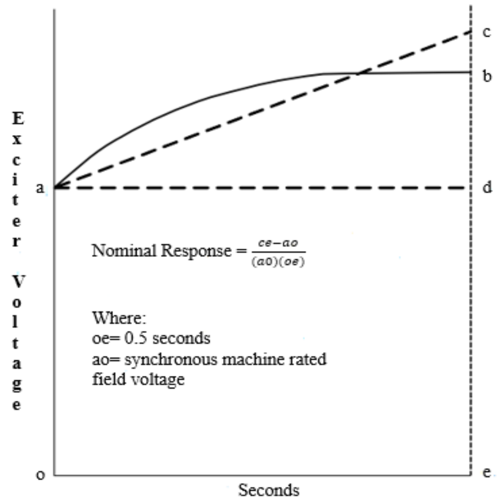

Figure2: Excitation System Nominal Response. Capture taken from IEE 421 standard.

The response ratio is affected by both the time it takes for the exciter to force to ceiling voltage following a system fault or severe disturbance, and the magnitude of the ceiling voltage available at the output of the exciter [1,9]. For a brushless excitation system, the time it takes to reach ceiling voltage is determined by the natural time constant of the brushless exciter. The magnitude of the ceiling voltage is determined by the brushless exciter design, the exciter field circuit resistance (including a series-connected field limiting resistor, if any) and the permanent magnet generator (PMG) voltage.

For example, if the requirement is 0.5 response ratio, the required linearized voltage at 0.5 second can be determined using the equation per IEEE 421.1-2007, section 3.29 (See Figure 1).

$$Nominl\ response(or\ response\ ratio) = \frac{ce-ao}{ao*oe} \quad (1)$$

$$ce - ao = 0.5 * ao * 0.5 = 0.25 * ao$$

$$ce = 0.25 * ao + ao = 1.25 * ao$$

Therefore, in order to have a minimum response ratio of 0.5, the exciter output voltage linearized should rise to be at least 125 percent of the generator field voltage at rated conditions in 0.5 second or 1.25 per unit (where 1.0 p.u. is defined here as the generator field voltage at rated MVA, kV, and power factor).

Ceiling voltage is the maximum direct voltage in which the excitation system is able to supply from its output terminals under defined conditions [1].

Notes:

1. The no-load ceiling voltage is determined with the excitation system output disconnected.
2. The ceiling voltage under load is determined with excitation system loaded by the generator field.
3. For an excitation system whose supply depends on the synchronous machine voltage and (if applicable) current, the nature of power system disturbances and specific design parameters of the excitation system and the synchronous machine influence the excitation system output. For such systems, the ceiling voltage is determined considering an appropriate voltage drop and (if applicable) current increase.
4. For excitation systems employing a rotating exciter, the ceiling voltage is determined at rated speed.

An exciter's response time is the time it takes to force from rated voltage to ceiling voltage [1]. In order to determine the exciter's response time, the ceiling voltage of the exciter needs to be known, and in order to determine the ceiling voltage, the maximum current the PMG can provide to the exciter field winding after rectification and transient stabilization must be determined. Figure 3 shows a PMG voltage regulation curve where the x-axis is rectified dc current supplying the exciter field, and the y-axis is rectified dc voltage. Note that the field voltage decreases as field current increases.

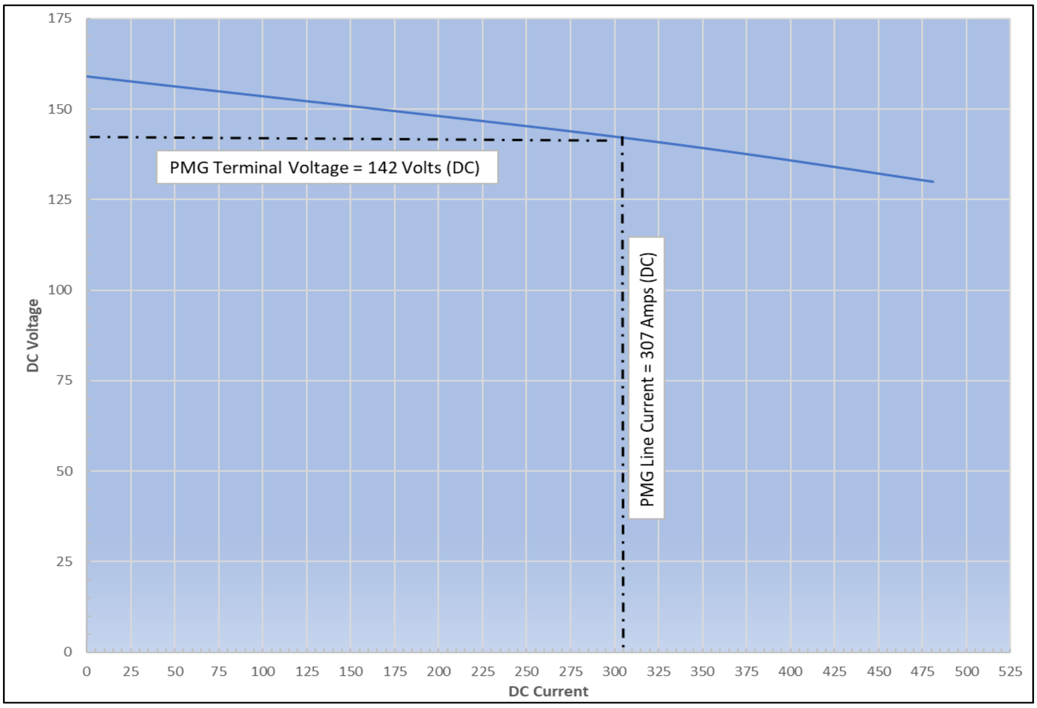

Figure 3: Conventional PMG Regulation Characteristic Curve

Based on the excitation requirement which (235 A dc and 498 V dc) a PMG with sufficient voltage and current capacity was selected and a summary of its parameters is provided in Table 2.

Table 2: Conventional PMG nameplate parameters

PMG Rating [kVA]	76
PMG Number of Phases	3
PMG Frequency [Hz]	420
PMG Number of Poles	28
PMG Rotational Speed [RPM]	1800
PMG No Load L-L Voltage [V-rms]	135
PMG Full Load L-L Voltage [V-rms]	125
PMG Full Load Phase Current [A-rms]	350
PMG Power Factor	0.95

The excitation requirement is based on the generator conditions which is provided in table 3. Since generator sizing is based on MVA rather than MW, the lower the power factor, the larger the generator. The power factor also determines the amount of reactive MVA capability the customer receives for a particular turbine megawatt output. For reactive capability from the generator design viewpoint, the power factor is a measure of the rotor current capability. The lower the power factor, the higher the reactive capability and the more rotor current capability is required. The nameplate-rated power factor is just 1 point out of the entire operating range for the generator.

Table 3: Generator operating conditions

MVA	1356
MW	1220
PF	0.9
kV	24
Rotational Speed [RPM]	1800
Number of Phases	3
Frequency [Hz]	60
PSIG	75
Generator rotor field resistance @ 75 °C [Ω]	0.0524

Based on Figure 3, 307 A is the PMG rectified ceiling current applied to the exciter field. Using this value, we can find the exciter output voltage (Ceiling Voltage) corresponding to that current value on the exciter constant-resistance load saturation curve shown in Figure 4. Note that 3 pertinent curves are provided in Figure 4 that correspond to a conventional brushless exciter.

- No-load exciter saturation curve. This curve shows the relationship between the exciter field current and the resulting exciter dc output voltage with the exciter output in the open-circuit condition (i.e., not connected to the generator field).

- Exciter air gap line. The extended straight-line part of the exciter no-load saturation curve, thus neglecting the effects of magnetic saturation.
- Exciter constant resistance saturation curve. This curve shows the steady-state relationship between the exciter field current and the resulting exciter dc output voltage with the exciter output connected to the generator field resistance.

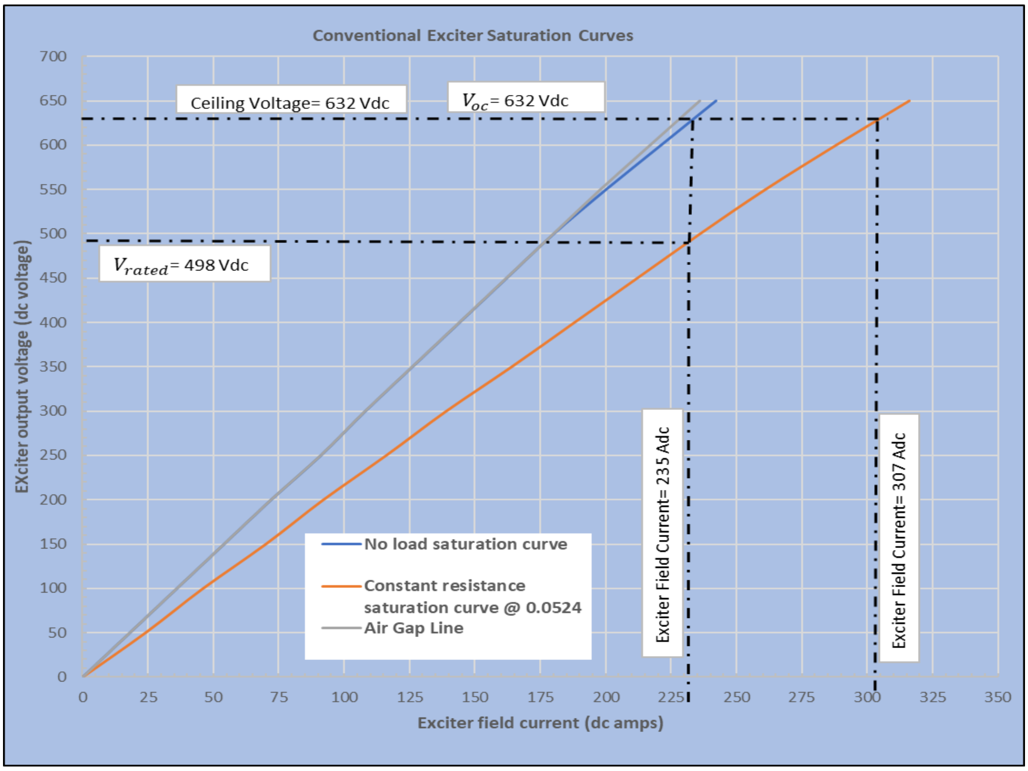

Figure 4: Conventional Brushless Exciter Saturation Curves

Figure 4 shows 632 V ceiling voltage on the constant resistance saturation curve at 307 A exciter field ceiling current, which is ultimately the ceiling voltage that is used to determine the response time. The response time depends on the exciter open circuit time constant (Te) and can be calculated using the following equation:

$$\mathrm{Te} = \frac{L_f}{R_{f} + R_{ext}} \qquad (2)$$

$$L_f = \left(\frac{{N_P}^2 P L_P}{10^8}\right)\left(\frac{C_P \pi \lambda_a}{2} + \lambda_a\right) \qquad (3)$$

$$R_f = \frac{\rho \, * MTN_P P}{10^6 \, q_C} \qquad (4)$$

Where:

N_P is the number of turns per pole,

P is the number of stator poles,

L_P is pole body length,

C_P is pole constant,

π is approximately 3.14159,

λ_a is air gap specific permeance,

ρ is resistivity at 75 °C,

MT is mean turn of field coil,

q_C is field conductor cross section

Table 4 provides the machine constants, rating and electrical parameters of the selected conventional brushless exciter. These parameters will be used to calculate the inductance and the resistance which are needed in order to calculate the response time.

Table 4: Conventional brushless exciter machine constants and electrical parameters

Parameter	*Value*	*Unit*
Voltage	525	Volts (DC)
Current	10476	Amps (DC)
kW	5500	
N_P	24	
P	20	
L_P	50	inch
C_P	.675	
λ_a	34.89	
P	$0.825x10^{-6}$	Ohm-inch
MT	108	inch
q_C	.216	in^2
L_f	0.269	Henry
R_f	0.198	Ohm
R_{ext}	0.1410	Ohm

L_f is the self-inductance of the exciter field, R_f is the exciter field resistance and R_{ext} is the external series field limiting resistor and was selected based on the exciter field resistance required in order to meet ceiling voltage requirement which for this application is 632 Volts. Note equations 3 and 4 were used to calculate L_f and R_f

$$L_f = \left(\frac{24^2 * 20 * 50}{10^8}\right)\left(\frac{.675 * 34.89}{2} + 34.89\right)$$

$L_f = .269$ H

$$R_f = \frac{.825 * 108 * 24 * 20}{10^6 * .216}$$

$R_f =$ .198 ohm

Using equation 2, Te is as follows:

$Te = \frac{0.269}{0.198 + .141} = 0.793$ s

On the exciter constant-resistance load saturation curve, find that voltage V_{rated} (or closest possible value) and track upwards vertically (same field current, different voltage) to find the voltage V_{oc} on the open circuit saturation curve. See Figure 4. Now, to calculate the loaded time constant, use the following equation:

$$T_{load} = Te * \left(\frac{V_{rated}}{Voc}\right) \qquad (5)$$

$T_{load} = 0.793 * \left(\frac{498V}{632V}\right) = 0.625\ s$

Once the loaded time constant has been determined, the following formula can be used to determine the time it would take the system to go from rated field current to ceiling current, but first we must calculate the field current at loaded circuit condition. In other words, when time $T_{load} = .625\ second.$

$$I(t) = I_{rated} + \left(I_{ceiling} - I_{rated}\right)\left(1 - e^{-t/T_{load}}\right) \qquad (6)$$

Note when the AVR calls for ceiling voltage, the exciter field voltage will equal the rectified PMG voltage. According to Figure 3, the PMG rectified dc voltage is 142 V. At this point, the exciter field current will start rising exponentially from 235 Adc to (142 V/.339 Ω)= 419 Adc with an exponential time constant of 0.625 s. Using equation 6, it takes about 0.307 s for the system to go from rated field current to ceiling current 47.8 A

$307 = 235A + (419A - 235A)\left(1 - e^{-t/0.625}\right)$

t= .307 s

The calculated response of the exciter field current based on the loaded time constant (using equation 6), its corresponding exciter output field current values determined using the load saturation curve and the exciter output current rise is shown below in Figure 5.

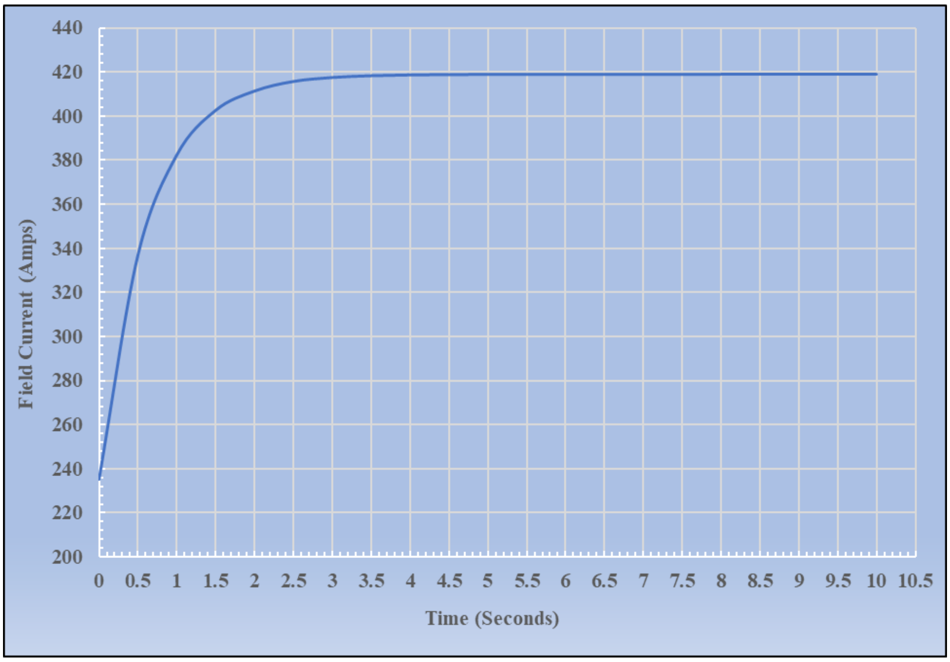

Figure 5: Conventional Brushless Exciter Field Current Rise Characteristic Curve

A high initial response (HIR) excitation system is defined as a system that has a voltage response time of 0.1 second or less. Thus, a conventional response brushless excitation system does not meet the requirement of an HIR system. Note a voltage response time is the time in seconds for the excitation voltage to attain 95% of the difference between the ceiling voltage and rated load field voltage under specified conditions [1]. An HIR excitation system represents a high response and fast acting system.

An exciter ceiling voltage is defined as the maximum voltage an excitation system can attain under specified conditions. It is an indication of field forcing capability of the excitation system [1]. Higher ceiling voltage tends to improve transient stability. Nominal exciter ceiling voltage occurs with the exciter output connected to the generator field, and thus the dc constant resistance load saturation curve applies. Most brushless exciters are designed based on a 120% nominal ceiling voltage based on the exciter dc voltage rating.

3. Modifications to Reduce Response Time to Ceiling

In order to reduce the response time of a brushless exciter, the ac exciter stator, PMG, and automatic voltage regulator (AVR) will require modifications. The bulk of the exciter remains the same in such a conversion. The ac exciter rotor including its electrical steel laminations and coils are retained with no changes. In addition, the diode wheel and its associated components are also retained with no changes. The following sections describe the required exciter modifications.

3.1 Reduce exciter field winding inductance

The purpose of the AC stator is to create a stationary magnetic field around the rotor. This stationary magnetic field establishes an alternating field in the exciter rotor. The AC stator field coils are comprised of hundreds of layers of electrical steel laminations stacked together to create each pole, which is then wrapped with several layers of insulated copper wire to carry the field current through a given number of turns.

By reducing the number of turns, the inductance of the field winding will be lowered. Note the inductance is proportional to the number of turns squared per equation 3. Note the number of turns were reduced from 24 to 10 which is a ratio of 2.4 to 1 [10].

$$L_f = \left(\frac{10^2 * 20 * 50}{10^8}\right)\left(\frac{.675 * 34.89}{2} + 34.89\right)$$

$$L_f = 0.046\, H$$

While the resulting change in inductance aids in the requirement to reach ceiling current in under 0.1 second or less, changes in the ac exciter stator (field) winding configuration must maintain the desired magnetic circuit flux density in the field poles and ac exciter armature. The changes involve replacing the field winding conductors with a larger cross section to carry a higher current with a significantly lower number turns. The net effect will be a significant reduction in both the exciter field inductance and resistance. The major portion of the reluctance of the magnetic circuit is the air gap. Larger air gap implies larger reluctance. Note there's a direct proportionality between the magnetomotive force (mmf) and the air gap; for a given amount of mmf, certain amount of flux is required. If the air gap is increased, the reluctance and the mmf will also increase. To get the same amount of flux, more mmf would be required in order to compensate for the increase of reluctance as a consequence of increasing the air gap [10]. Table 5 shows updated values to the electrical parameters in Table 4 in order to convert the conventional exciter presented in this paper to HIR. Note the rating of the exciter will remain the same.

Table 5: HIR brushless exciter machine constants and electrical parameters

Parameter	*Value*	*Unit*
Voltage	525	Volts (DC)
Current	10476	Amps (DC)
kW	5500	
N_P	10	
P	20	
L_P	50	inch
C_P	.675	
λ_a	34.89	
P	$0.825\text{x}10^{-6}$	Ohm-inch
MT	123	Inch
q_C	.375	in^2
L_f	0.046	Henry
R_f	0.054	Ohm
R_{ext}	0	Ohm

Normally, the resistance of a conventional brushless exciter field winding is around 1 Ohm. If the number of turns per pole are lowered, the resistance will also decrease, as well as a bigger cross section to carry the required increase in current. These two effects will lower the field winding resistance: a bigger cross section and lowering the number of turns. Note the total length of the coil is shorter because there are fewer turns and the cross section is bigger; therefore, both effects reduce the resistance. Note the new resistance shown in Table III was calculated using equation 4:

$$R_f = \frac{.825 * 123 * 10 * 20}{10^6 * .375}$$

$$R_f = 0.054 \text{ ohm}$$

The existing field limiting resistor would not be needed and would be removed. Thus, it’s equated to zero. Also, if there are any damper bars in the exciter stator poles, those would also be eliminated so as not to impede the extremely fast changes of flux during forcing conditions. Similarly, to avoid induced stray currents which could oppose fast changes in flux, if there exists a solid magnetic steel frame upon which the poles are mounted, that would also require replacement with a laminated magnetic steel frame with the same dimensions, resulting in the same air gap between the stator and rotor.

3.2 Laminations in magnetic circuit path (poles and frame)

In order to go from a conventional brushless exciter to HIR, flux in the stationary poles must change quickly. If the exciter has solid poles, where there are no laminations, there will be eddy currents which will create their own opposing mmf and consequently, the increasing flux will be opposed by the new mmf created by such phenomenon. Thus, it’s crucial that the poles and the frame for an HIR exciter be laminated. When the flux passes through the north and south poles, the magnetic field has to go through the frame as well. Note the poles are bolted unto the frame. Therefore, if the frame is not laminated, then there will be opposing flux. Applying flux at a rapid pace in a non-laminated conductor will generate eddy currents which will oppose the flux from increasing rapidly [10].

3.3 AC Exciter Rotor and Diode Wheel

The dimensions and electrical characteristics of the ac exciter rotating armature and diode wheel are retained. They will not be impacted by the modification. Note the ac exciter rotor consists of the armature winding and core. The armature core is normally built of high grade, non-aging silicon steel laminations. Both sides of the laminations are treated with a suitable insulating material to prevent short circuiting the laminations. The armature winding consists of formed interchangeable coils. Eddy currents are reduced to a minimum by selection of conductor and strand size.

The diode wheel components such as diodes, fuses, capacitors, etc. remain the same since the excitation requirement of the main generator will remain the same. The selection of these components was based on the excitation requirement of the generator and if the generator continues to operate at the same rating, it’s not necessary to change or swap these components.

3.4 PMG (Rotor and Stator)

The permanent magnet generator (PMG) is typically located at the outboard end of the exciter. It provides unregulated 420 Hz ac power for the voltage regulator power amplifier and auxiliary circuits. The PMG consists of rotating permanent magnets mounted on the end of the exciter shaft, and a stator-mounted armature for three-phase operation. The PMG is ventilated by air which is part of the exciter ventilation.

The magnets of the PMG rotor are stabilized during the manufacture of the PMG to prevent changes in the output voltage from any short circuits on the system. The existing PMG will not be capable of providing sufficient voltage or current to the AVR for supplying the new required exciter dc field voltage and current for an HIR application. Thus, it needs to be replaced with a PMG that has greater capacity. The ac exciter field will require more current, and thus a larger PMG is needed to provide the required rectified current from the AVR. Also, a larger PMG voltage is needed for the AVR to be able to provide a sufficiently high output voltage to the exciter field to achieve a sufficiently fast rate of rise of exciter field current [4]. See Table 6 for the rating of the HIR PMG.

Table 6: HIR PMG nameplate parameters

PMG Rating [kVA]	321.15
PMG Number of Phases	3
PMG Frequency [Hz]	420
PMG Number of Poles	28
PMG Rotational Speed [RPM]	1800
PMG No Load L-L Voltage [V-rms]	350
PMG Full Load L-L Voltage [V-rms]	292
PMG Full Load Phase Current [A-rms]	635
PMG Power Factor	0.95

3.5 Automatic voltage regulator (AVR)

The AVR will require some assessments and changes in order to function properly as part of the HIR brushless excitation system. This includes:

- AVR ac voltage input from PMG. The AVR will need to accommodate the new higher PMG voltage.
- AVR dc output current to exciter field. The AVR will need to provide the larger continuous dc exciter field current at rated generator conditions and also the higher exciter field current at ceiling conditions.
- Instantaneous exciter field current limiter. When configured for HIR application and supplied by the new higher voltage PMG, the AVR will have the voltage forcing capability to increase the exciter field current above an amount that is significantly more than is required for ceiling conditions. Therefore, the AVR must be equipped with an instantaneous exciter field current limiter function and protection

which assures that the exciter field current will not exceed its ceiling value.

- Tuning for fast small-signal response. The AVR must have tuning capability to achieve fast excitation system response in its linear range as well as fast large-signal response.

4. Response of HIR Brushless Exciter

The high initial response (HIR) brushless excitation system obtains its fast small-signal response by application of a time constant compensation (current regulator) circuit in the voltage regulator control. This circuit provides a feedback path around the brushless exciter time constant to lower the effective exciter time constant. The amount of time constant compensation can be adjusted with the gain setting on the current regulator module. A higher gain will result in a lower effective time constant [3].

Small-signal performance can be measured by either a transient response or frequency response test. A transient response test of an excitation system is normally made by applying a small step-change in input to the voltage regulator and measuring the time response of the output (exciter output voltage, exciter field current, or generator terminal voltage deviation). A frequency response test is performed by applying a small sinusoidal signal into the voltage regulator and measuring the gain and phase angle relationship of the input vs. output signals as a function of input signal frequency [5].

According to IEEE Standard 421-2021, a HIR excitation system must be able to reach 95% of the difference between ceiling voltage and rated load field in 0.1 second or less [1]. The HIR brushless excitation system achieves fast large-signal response by the application of a PMG and power amplifiers whose voltage capability greatly exceeds that required to maintain exciter ceiling voltage in the steady-state condition. For large voltage regulator input signals, the large power amplifier voltage capability forces the exciter field current (and thus the exciter output voltage) to rise at a very fast rate. When the exciter reaches ceiling conditions, instantaneous current limiter circuitry acts to limit this forcing once ceiling is reached, so as not to exceed the exciter maximum capability [3], [5].

Typical HIR brushless exciter saturation curves are displayed in Figure 6, and they are very similar to those of a conventional brushless exciter with the exception that more field current is required for the same amount of exciter output voltage. The curves show the relationship between the exciter field current and the dc output voltage of the exciter.

- The air gap line shows the linearized relationship between the exciter field current and the rectified dc exciter output voltage terminals, ignoring effects from magnetic saturation and load.
- The no-load exciter saturation shows the relationship between the exciter field current and the rectified dc exciter output voltage at open circuit measured across the exciter output terminals, including the effects of magnetic saturation ac exciter rotor and stator components.
- The constant resistance saturation curve shows the relationship between the exciter field current, and the exciter dc output voltage loaded with a constant resistance at the exciter output terminals. It includes the loading effects of the load resistance, magnetic saturation in the exciter components and

effects of diode commutation in the rectifier wheel.

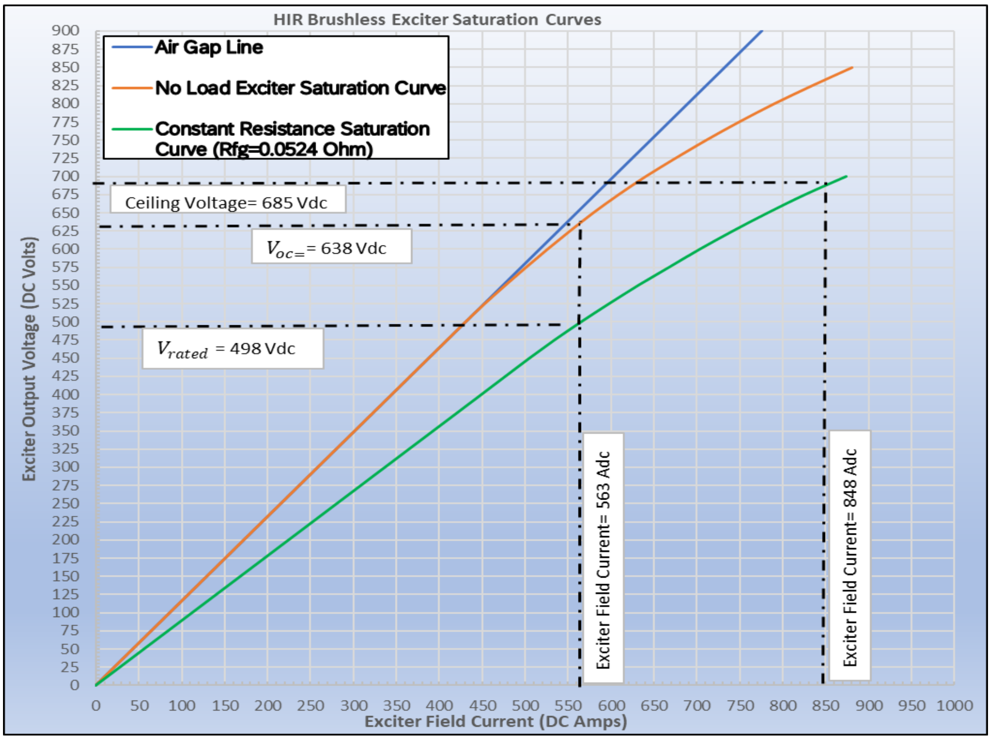

Figure 6: HIR Brushless Exciter Saturation Curves

The conventional brushless exciter in this paper was converted to HIR by calculating the response time as described in this paper. A PMG with a higher voltage and current rating is required in order to do the conversion, as shown in Fig. 7 with a new larger exciter field ceiling current requirement. Note that the field ceiling current requirement has increased from 307 A to 848 A.

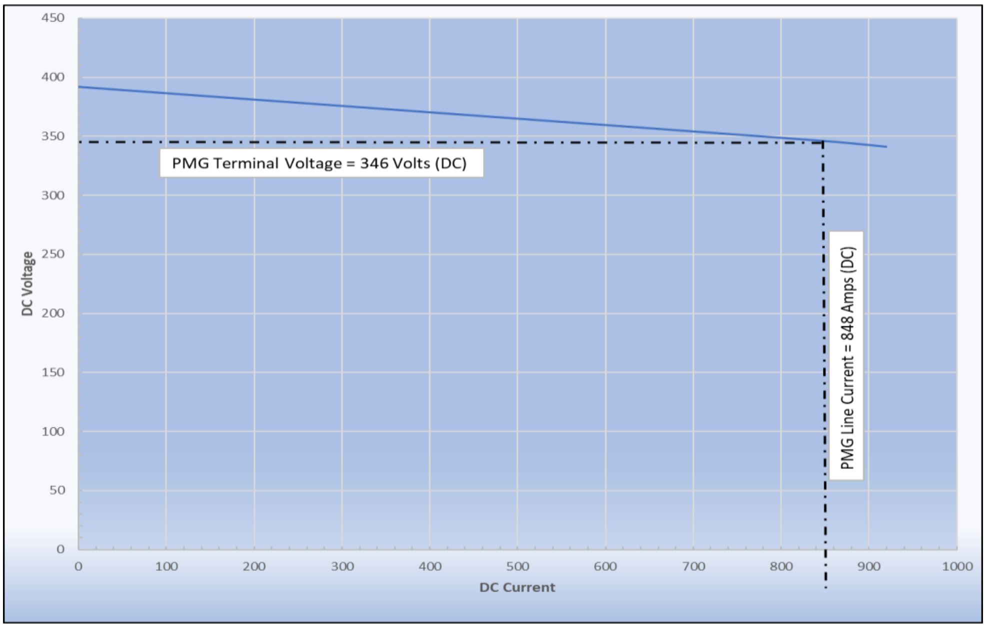

Figure7: HIR PMG Regulation Characteristic Curve

The new higher exciter field ceiling current is 848 A, which intersects the rectified PMG regulation curve at 346 Vdc. Based on the HIR exciter constant resistance saturation curve shown in Fig. 6, the new exciter output ceiling voltage is 685 Vdc. With $L_f = 0.046$ H, $R_f = 0.054\, ohm, R_{ext} = 0$ and using equation 2:

$$Te = \frac{0.0466}{0.054 + 0} = 0.863 \text{ s}$$

On the HIR exciter constant-resistance load saturation curve in Fig. 6, $V_{rated} = 498\, Vdc\ and\ V_{oc=}$ 638 Vdc. Using equation 5 to calculate the loaded time constant, the result is the following:

$$T_{load} = 0.863 * \left(\frac{498}{638}\right) = 0.674 \text{ s}$$

Once the loaded time constant was determined, equation 6 was used to determine the time it would take the system to go from rated field current to ceiling current, but first the field current at open circuit condition was calculated and found to be $T_{load} = 0.674\, s$. Note when the AVR calls for ceiling voltage, the exciter field voltage will equal the rectified PMG voltage. According to Fig. 7, the PMG rectified dc voltage is 346 V. At this point, the exciter field current will start rising exponentially from 563 Adc to (346V/0.054 Ω) = 6407 A with a time constant of 0.674 s as shown in Fig. 8 before being limited when the ceiling current 848 Adc is reached.

Solving for time t in the equation below, it takes about 0.031 s for the exciter field current to increase from rated exciter field current (563 A) to ceiling current (848 A), which is within IEEE definition of required response time for an HIR exciter.

$$848 = 563 + (6407 - 563)\left(1 - e^{-t/0.674}\right)$$

t = 0.034 s

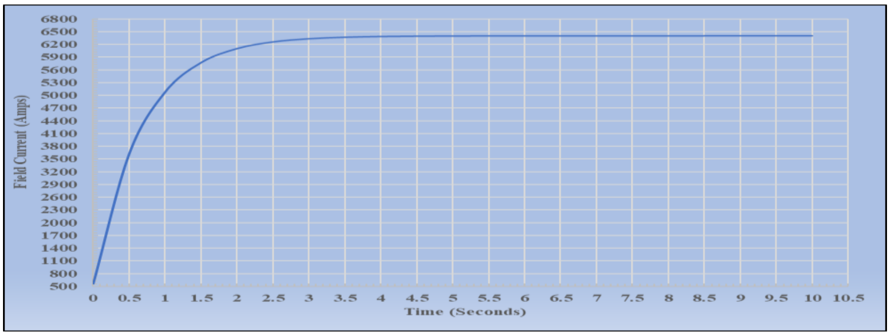

Figure 8: HIR Brushless Exciter Field Current Rise Characteristic curve

5. Summary and Conclusion

Converting a conventional brushless exciter to a high initial response (HIR) exciter is possible with modifications to the ac exciter stator field, PMG and AVR. A high initial response brushless exciter is designed for a fast response similar to that of a static excitation system yet retains the beneficial features of a brushless excitation system, such as a rotating rectifier, no collector rings, and all power derived from the shaft operation. The overall excitation system response involves a combination of ceiling voltage and response time. A conventional exciter has a typical response time of 0.5s or so. As outlined in this paper, making appropriate changes can improve the response time and thus make it an HIR exciter. Examples are provided in this report with solid calculation methods with response time calculated for both a conventional and HIR brushless exciter, which demonstrate proposed changes that are required to convert a conventional brushless exciter into an HIR exciter having a response time of 0.1s or less is valid.

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