

Using Snubber Circuits in a Brushless Exciter Will Reduce Voltage Commutation Spikes

Esnick Felissaint^a*, Kalpathy Sundaram^b

^aEsnick Felissaint is with Siemens-Energy, 4400 N Alafaya Trl, Orlando, FL. 32826 ^bKalpathy Sundaram is with the University of Central Florida, 4000 Central Blvd, Orlando, FL. 32816 ^aEmail: esnick.felissaint@siemens-energy.com ^bEmail: kalpathy.sundaram@ucf.edu

Abstract

In a brushless exciter with a multi-phase bridge rectification system, diodes open and close periodically. When a diode turns off, a commutation voltage spike is generated by the internal AC winding inductance of the machine. Voltage spikes can be detrimental to the health of the diodes that are operating in the machine. A diode can fail short in the reverse direction if its reverse recovery voltage is exceeded, or it can fail open due to excessive current in the forward direction. Voltage commutation spikes are known to occur with various amplitude in shaft voltage to ground with static excitation systems and exciter field voltage to ground in brushless excitation systems. This paper evaluates the phenomena of voltage commutation spikes and presents a snubber circuit as a robust solution that can reduce the amplitude of the spikes. Consequently, prolonging the life of the diode and allows it to function as designed at optimal level.

Keywords: Brushless exciter; diode; rectifier; commutation spike; forward biased; reversed biased; P-N junction; anode; cathode; forward voltage; repetitive peak reverse voltage; fuse; reverse recovery time; capacitor.

Received: 3/5/2024 Accepted: 6/5/2024 Published: 6/17/2024

* Corresponding author.

1. Introduction

A brushless exciter includes an AC machine with a stationary field winding and rotating armature that feeds a rotating multi-phase bridge rectifier [1]. In the bridge rectification system diodes turn on and off at a rate which depends upon the frequency of the AC voltage which supplies the bridge. If a forward bias voltage is applied to a diode, it turns on and carries some forward current. After reverse bias is applied to the diode, it does not turn off immediately but rather stays on for some time and reverse current increases until p~n transition clears off excess carriers [7]. When a diode turns off, a commutation voltage spike is induced across the diode by the large di/dt occurring through the diode and the internal AC winding inductance. This voltage spike can be detrimental to the health of the diodes operating in the machine [7]. Diodes are susceptible to commutation voltage spikes if snubber circuits are not applied for spike amplitude reduction. Voltage spikes pose a great risk to the diode while the machine is in operation, and consequently can lead to a forced outage, if not addressed. Commutation spike is a common phenomenon in brushless exciters and there are ways to minimize its impact. The amplitude of the spike depends on diode properties, circuit as a mean to mitigate its impact are presented in this paper.

2. Brushless Exciter Description

The brushless excitation system with its rotating armature and diode wheel and the absence of brushes and slip rings has proven to be an extremely reliably means of generator excitation over the years. The typical brushless excitation system utilizes a three-phase permanent magnet generator (PMG) which supplies ac power to a voltage regulator thyristor power bridge[1]. The dc output of the thyristor power bridge is connected to the brushless exciter field winding, which is comprised of multiple north-south stationary field poles with the field windings around the poles connected in series. The exciter field poles provide magnetic excitation to a rotating three-phase armature, which sends its ac output in the same rotating frame of reference to a rotating six-pulse full bridge diode wheel rectifier, with the dc output of the diode wheel sent directly to the generator field winding.

The brushless exciter is a rotating machine that derives its excitation power from shaft rotation [1]. The brushless excitation system consists of a rotating ac armature with a stationary dc field and a rotating diode wheel. The rotating armature is excited by a low-power stationary dc field (typically supplied by a controlled rectifier bridge in the voltage regulator). The output of the armature is rectified by a rotating diode rectifier assembly, which supplies dc excitation to the generator rotor field winding without the need for brushes or slip rings. The brushless exciter dc output to the generator field is controlled by adjusting the exciter dc field current, which in turn determines the ac voltage in the rotating armature and the dc voltage at the output of the rotating rectifier assembly. The exciter dc field is supplied by the voltage regulator, either under automatic or manual control. Exciter field power is a very small percentage (on the order of 1%) of generator field power supplied by the exciter as shown in Figure 1.



Figure 1: A typical Conventional Brushless Exciter Diagram

3. Diode and Bridge Rectification in a Brushless Exciter

A conventional solid-state diode is a type 1 switch. It has two terminals, known as the anode and the cathode. Internally, a simple diode consists of a single P-N junction within a crystal of silicon [2,3]. The anode terminal connects to the P side of the junction, and the cathode connects to the N side. When the anode or P side is positive with respect to the cathode or N side, the diode conducts forward current with a relatively small voltage drop. A semiconducting device that has single P-N junction correspond to the characteristic shown in Figure 2 [4]. When the diode is forward biased (anode positive with respect to cathode), its forward current ($I=I_F$) increases rapidly with increasing voltage. That is, its effective resistance becomes very low. When the diode is reverse-biased (anode negative with respect to cathode), its reverse current ($-I=I_R$) is extremely low. This is only valid until the breakdown voltage V_{BR} , has been reached. When the reverse voltage is slightly higher than the breakdown voltage, a sharp rise in reverse current will manifest. Once the breakdown voltage has been compromised, the device will not function as designed. It will be in a defective state.



Figure 2: P-N diode IV characteristic.

Performance specifications for diodes are as follows [5,7]:

- Junction operating temperature: Junction operating temperature is the range of temperature over which a diode is designed to operate. Like all electronic components, diodes have a maximum operating temperature. As the junction temperature rises, the reliability will fall over the long term. If the maximum junction temperature is exceeded, the diode is likely to fail.
- **Reverse recovery time**: Reverse recovery time is the time taken for the reverse current to reach a specified level when the reverse voltage is applied after the diode has been conducting in the forward direction.
- **Repetitive peak reverse voltage**: Repetitive peak reverse voltage is the maximum allowable value of reverse voltage that can be repeatedly applied to the reverse direction of the diode. Note when the polarity is reversed, a large reverse voltage can be applied but only a small reverse leakage current will flow.
- Peak forward surge current: The maximum permissible surge current in a forward direction having a specified waveform with a short-specified time interval (i.e., 10ms) unless otherwise specified. It is not an operating value. During frequent repetitions, there is a possibility of change in the device's characteristic.
- **Reverse current (leakage current):** The current which flows when reverse bias is applied to a semiconductor junction. If a perfect diode were available, then no current would flow during reverse biased operation. It is found for a real P-N junction diode, a very small amount of current flow in the reverse direction as a result of the minority carriers in the semiconductor. The level of leakage current depends upon three main factors: the reverse voltage, the temperature. and the semiconductor material (lower in silicon vs. germanium).
- **Forward voltage:** Forward voltage is the voltage across the diode terminals which results from the flow of current in the forward direction.
- Forward current: Forward current is the current flowing through the diode in the direction of lower resistance.

4. Three-phase Diode Rectifiers

Diodes are used in a brushless exciter to convert AC voltage to DC, and the quantity of diodes required depend on the rating and excitation requirements of the main generator. Diodes are often connected in parallel in order to meet such excitation demand. In large generator applications the quantity of diodes connected in parallel may vary anywhere from 4 to 20 diodes per phase per polarity. A good design philosophy requires that the rotating rectifier should be capable of successfully operating with 25% of its diodes out-of-service. This requirement dictates that the diodes shall be able to operate under a maximum current load of the brushless exciter. In designing a rotating machine such as an exciter, the generator field requirement or excitation requirement will be specified.

An exciter must be designed such that both the transient and continuous conditions can be handled by the exciter. After determining the machine's rating both at continuous and at transient conditions, the number of

diodes can be determined. In determining the required output capability of the exciter, the number of diodes must not include the redundancy circuits diodes. Also, the diodes employ fuses to remove any failed diodes, which typically fail in a shorted condition. Each diode should have a high enough reverse recovery voltage to satisfy the ceiling requirement of the exciter as well as the fuse voltage at ceiling conditions. Fuses must have enough capacity to carry steady state current as well as ceiling and surge related currents. The function of a diode fuse is to isolate any shorted diode from the circuit in order to protect the remaining exciter circuits including the AC exciter armature. The fuse must limit the let-through current, while the diode is shorted, to a sufficiently low value so that the current feeding to the diodes and fuses of other phases do not become damaged. The fuse must also be able to withstand the arc voltage which is generated when a diode shorts and the fuse opens during any exciter operating condition including ceiling.

Table 1 is a list of some of the brushless exciters in the fleet with different quantities of diodes based on the exciter frame size.

Frame Size	Diode per polarity	Diode per phase (3 phases)	Total number of diodes	
Frame 06	06	12	36	
Frame 08	08	16	48	
Frame 12	12	24	72	
Frame 16	16	32	96	

Table 1: Exciter Frame Size and Diode Quantities

5. Analysis of Commutation Spikes

The function of each diode in the diode wheel rectifier bridge is to conduct current when in the forward biased state and to switch to a blocking state during the time that the voltage is reversed biased. Because there is inductance in the ac exciter armature winding and the current in this inductance cannot change instantly during commutation, there is a time period during which each diode transitions from the "on" state to the "off" state. The forward-bias voltage drop exhibited by the diode is due to the action of the depletion region formed by the P-N junction under the influence of an applied voltage [7]. If no voltage is applied across a semiconductor diode, a thin depletion region exists around the region of the P-N junction, preventing current flow.

The depletion region is almost devoid of available charge carriers, and acts as an insulator. If a reverse-biasing voltage is applied across the P-N junction, this depletion region expands, further resisting any current going through it. Conversely, if a forward-biasing voltage is applied across the P-N junction, the depletion region collapses and thus becoming thinner. The diode becomes less resistant to current flowing through it in order for a sustained current to go through the diode; though, the depletion region must be fully collapsed by the applied voltage. This takes a certain minimum voltage to accomplish, called the forward voltage. Note that every diode has a minimum forward voltage drop which is the turn "on" voltage of the diode [6].



Figure 3 graphically shows the transition of the diode current during the commutation period [8].

Figure 3: Current and voltage characteristics during commutation period.

Initially the diode carries its normal forward current, which then starts decreasing at the instant in which the voltage in its phase is exceeded by the voltage in one of the two other phases. At this point the diodes in both phases are in the "on" state, and the current in the diode reduces toward zero with a slope di/dt equal to $\Delta V/L$, where ΔV is the difference in the armature phase voltages and L is the inductance in the exciter armature winding. There is a direct proportionality or relationship between ΔV and di/dt. During the initial portion of the commutation period when ΔV is small, di/dt is also small. As commutation progresses, ΔV continues to increase, and thus di/dt also increases.

This condition continues even as the current through the diode reverses direction (at point A in Figure. 3), because a certain amount of charge remains in the diode junction, which must be removed before the diode can stop conducting and turn off. Thus, between points A and B in Figure 3 there is reverse current flowing through the diode and the armature phase inductance. When all the charge is removed from the diode junction, as depicted in point B, the reverse current is at its maximum value I_{rev} , and the reverse recovery period begins, which means the depletion region will expand. During this reverse recovery period tb, the reverse biased diode, switches to the "off" state, and its current and the current in the armature phase inductance quickly reduced to zero. The armature inductance reacts to this steep change in current di/dt with a voltage spike corresponding to L*di/dt across the armature inductance, and thus also across the diode, creating a reverse voltage "spike" as shown in Figure 3. If excessive, such a voltage spike can adversely impact the functionality of the diode. In order to reduce the resulting voltage spikes across the diodes during commutation, a resistor-capacitor voltage suppression "snubber" network is typically connected across the diodes [9,10].

6. Measurement of Commutation Spike

Measurements were performed on a stationary, three phase bridge rectifier circuit, whose diode and ac voltage

source parameters were matched as closely as possible to those of a standard brushless exciter. The test setup is shown in Figure 4. The effect on the spike voltage of various voltage suppression (snubber) networks was measured, as well as the effects of some of the circuit parameters.

The main purpose of the test was to determine if adding a snubber circuit in series with a diode in a brushless exciter will reduce the commutation spike that it is likely to experience during operation. Additional tests were also performed to determine other effect of certain circuit parameters. The following is a summary of the objective of the test.

- 1. To determine if the snubber capacitance per diode could reduce voltage commutation spike.
- 2. To determine the effect of the various circuit parameters (damping resistor, load inductance, load current, etc.) on the commutation spike voltage.
- 3. To show the effect on the spike voltage for various types and classifications of diodes.

Figure 4 shows the test circuit that was utilized to measure the commutation spike voltages.



Figure 4: Three-phase test circuit.

The following is a description of the components that are part of the circuit in Figure 4.

A. Power Source

A permanent magnet generator (PMG) was used as the power source with the following rating:

- 387 Volts
- 635 Amps
- 403 kW
- 420 Hz
- 1800 RPM

The inductance per phase of this PMG is 3.78 µH, which falls in the range of the standard brushless exciter

alternator inductances (1.0 to 4.5 μ H/phase). The PMG was operated at 1500 RPM for most of the tests in order to obtain an output frequency of 350 Hz., which is in the range of the standard brushless exciter frequencies of 120 to 420 Hz.

B. Source Inductance

Inductance could be added to each leg of the PMG by means of air core reactors.

C. Rectifier

All components for a three-phase bridge rectifier were mounted onto a wooden panel. Each diode was mounted onto a heat sink, in series with fuse. Standard brushless exciter snubber capacitors were connected in series with carbon resistors to form the voltage suppression network. Ventilation was provided by a large test floor fan that forced air over the entire rectifier panel.

D. Load Circuit

The rectifier output was loaded into the series combination of air core reactors and standard test floor load racks. With the reactors connected for maximum inductance, the measured inductance of the load circuit was 0.13 Henries which is typical value for the generator field inductance.

E. Instrumentation

The instrumentation was connected as shown per Figure 4. A fast-rise oscilloscope was connected directly across diode "A". The calibration of the scope, and the compensation of the probe, were periodically checked. A thermocouple, not shown on Figure 4, was mounted on the case of diode "A", and was connected to a dial-indicating, quick response temperature sensor.

F. Test Procedure

Due to insufficient cooling of the heat sinks, the rectifier could carry full load current for only about 25 seconds before the diode case temperature reached its upper safe limit. Therefore, it was necessary to remove the load after every measurement was taken to allow the diode case to cool to room temperature. This cooling period did not increase the total test time required, because during this interval, the rectifier circuit was reconnected for the next "shot".

Since the magnitude of the spike voltage is a function of the diode junction temperature (see Figure 4), it was necessary to take each measurement at the same case temperature of 50 °C. After the diode case cooled to room temperature, the load was applied and the case temperature was observed until 50 °C was reached, at which point a measurement of the instantaneous voltage across reverse polarity diode "A" was taken. The meters were read at the same time that the measurement was taken. The breakers were then opened, and preparations were made for the next 'shot".

G. Discussion of results

The test results are plotted on Figures 5 to 13. In Figure 5 with all circuit parameters held constant, the spike voltage decreases as diode junction temperature increases.



Figure 5: Diode spike voltage vs diode case temperature.

In Figure 6 notice that the optimum snubber damping resistance is about 10 ohms and that a 50% reduction of capacitance increases the total diode inverse voltage at zero ohms by only about 6.1%.



Figure 6: Diode inverse voltage vs resistance at 300 Hz frequency.

The curves in Figure 7 are similar to those of Figure 6, except the frequency is 350 instead of 300 Hz. Figure 8 shows the effect of load current on inverse voltage. The lower curve shows the actual measured inverse voltage.

However, the PMG voltage drops with load. The upper curve is calculated from the lower and assumes the voltage to be constant after the 80-ampere point. In Figure 9 the effect of load inductance on the spike voltage is negligible.



Figure 7: Diode inverse voltage vs resistance at 350 Hz frequency.



Figure 8: Diode inverse voltage vs load current.



Figure 9: Diode inverse voltage vs resistance with various inductances

In Figure 10 the upper curve was measured at 360 Hz, 365 Volts while the lower two points were measured at 245 Hz, 255 Volts. If the two lower points are raised to consider the difference in voltage, then the difference between the two lower points and the upper curve should be due to frequency alone.



Figure 10: Diode inverse voltage vs resistance considering frequency and voltage.

The two curves in Figure 11 show the effect of source inductance on commutation spike voltage. Note that in this case the coordinates represent only the spike voltage, and not total inverse voltage. Note that the optimum damping resistance is a function of the source inductance.



Figure 11: Diode inverse voltage vs resistance and source inductance.

Surprisingly, the 789 diode in Figure 12, which is of p-type silicon, does not have a significantly higher spike than the 760 diode for values of damping resistance less than the optimum resistance which is of n-type silicon.



Figure 12: Diode inverse voltage vs resistance with various diodes.

In Figure 13 the diodes in the highest reverse recovery range, which is listed in the graph, could be expected to have the highest spike voltages. This was confirmed by test results. However, the diodes in the lowest test voltage range had higher spike voltages than the diodes in the intermediate range. These results indicate that the reverse recovery test voltage cannot be used to find the diodes that will have the lowest inherent spike voltage.



Figure 13: Diode inverse voltage vs resistance with various voltages.

In general, whenever the snubber capacitors were removed from the circuit, the diodes would fail. However, by reducing the load current, and thus the spike voltage, some measurements were successfully obtained with no snubber capacitor. Table 2 below is a comparison of two measurements taken under the same conditions except for including a snubber capacitor.

Table 2: Commutation spike voltage with and without capacitor

Diode	Current	Voltage	Capacitor Diode	Per	Resistance	Voltage Spike
788	310 Amps	388 Volts	0.0		0.0	1015 V
788	314 Amps	388 Volts	0.3 µf		0.0	533 V

Table 2 shows that the 0.3 μ F capacitor reduced the total instantaneous voltage imposed on the diodes from 1015 to 533 volts.

7. Conclusion

All parameters of the test circuit, including the load inductance but not including the load time constant, were matched closely to those of the standard brushless exciter line. Therefore, it is reasonable to assume that the voltages measured were of the same magnitude as those that appear across the diode in the three-phase bridge type brushless exciters. It is possible, however, that the leads to oscilloscope may have attenuated the high frequency components of the spike voltage. This effect was minimized by using shielded cable and by frequent checks of the probe compensation. In any case, the general shape of the curves and the relationship of the curves to each other (Figures 6 and 12) appeared to be correct.

In general, whenever the snubber capacitors were removed from the circuit, the diodes would be exposed and fail. This is indicative that the diode is not being protected by the commutation spike. However, by reducing the load current, and thus the spike voltage, some measurements were successfully obtained with no snubber capacitor. Note this would not be an optimal solution since some customers would desire to operate at full load due to high power demand in order to provide service to their customers. Thus, based on the results presented in table 2 it is safe to conclude that adding a snubber circuit in series with a diode in a brushless exciter will reduce the commutation spike that it will likely experience.

8. General Solution

In order to reduce the magnitude of the transient voltage spikes that occur during the reverse recovery period in a brushless exciter, a snubber circuit can be incorporated in series with the diode in the rectifier wheel bridge. Note the selected snubber circuit is typically comprised of a capacitor and a capacitor fuse, as shown in Figure 13.



Figure 13: Typical snubber circuit with capacitor and fuse.

The capacitor serves to reduce the voltage spike amplitude during diode turn-off by diverting current into the capacitor during the recovery period to reduce the di/dt in the armature inductance, and thus the L*di/dt which creates the voltage spike. The value of the snubber capacitor depends upon various conditions, such as the ac exciter armature inductance, armature voltage, generator field current, diode characteristics, and number of diodes in service per leg during the worst-case design condition.

Each capacitor is separately fused to limit the damage to the capacitor, diode, diode module, and other rectifier wheel components if the capacitor fails shorted. In this case the diode remains in service with the remaining capacitors in the leg performing the task of voltage suppression. When a diode turns on, there will be little or no forward voltage and thus little or no charge stored in a parallel snubber capacitor during the instant of diode turn-on. Thus, there is no need for a resistor in series with the snubber capacitor during this turn-on period in the case of a diode bridge. This improves the simplicity and the overall reliability of the design.

Snubber circuits appear to be a robust solution for any brushless exciter with high commutation spikes. There are some exciters operating in the fleet without them that could be vulnerable to commutation spikes.

Fortunately, based on experimental data presented in this report a snubber circuit can be implemented as a robust and viable solution. It will reduce the amplitude of commutation voltage spikes that the diodes can experience. Consequently, prolonging its life and render it to function as designed at optimal level.

References

- [1] IEEE Std. 421.1-2011, "IEEE Standard Definitions for Excitation Systems for Synchronous Machines"
- [2] S. M. Sze, Physics of Semiconductor Devices, 2nd ed. (Wiley, New York, 1981), Chap. 5.
- [3] B. J. Baliga, Silicon Carbide Power Devices, Singapore: World Scientific, 2005.
- [4] B. Van Zeghbroeck (2011). "P-n junctions: I-V characteristics of real p-n diodes". Retrieved 2020-11-02.
- [5] P. O. Lauritzen and C. L. Ma, "A simple diode model with reverse recovery", JEEE Trans. Power Electron., vol. 6, pp. 188-191, Apr. 1991
- [6] Kal, Santiram (2004). "Chapter 2". Basic Electronics: Devices, Circuits and IT Fundamentals (Section 2.5: Circuit Model of a P-N Junction Diode ed.). Prentice-Hall of India Pvt.Ltd.
- [7] Isaa Batarseh, Power electronics circuit analysis and design, 2nd ed., January 2018.
- [8] Somos, Istvan, "Commutation and destructive oscillation in diode circuits," Transactions of the American Institute of Electrical Engineers, vol. 80, May 1961
- [9] Wei-Li, Dai, Hai-Hong, Qin, Guo, Hong-Hao et al, "Analysis of commutation in three-phase rectifier of doubly salient electro-magnetic generator," Proceedings of the CSEE, vol 28,
- [10] Etto E. VonZastrow and James H. Galloway, "Commutation behavior of diffused high-current rectifier diodes," IEEE Transactions on Industry and General Applications, vol. IGA-1965.