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DYNAMIC RF POWER CONTROL FOR DIII-D ICH/FAST WAVE OPERATION*

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Abstract—**Thanks to the broadcast industry, high power transmitters between 10 MHz and 100 MHz in megawatts power range can be obtained at a reasonable price. Thus, we could take advantage of such development to use this frequency range for ion cyclotron and harmonics fast wave heating in the magnetic fusion energy research.**

Usually, antenna loading conditions can be fine tuned to meet the fusion plasma heating needs. However, the edge localized mode (ELM) during the plasma operation can cause up to 90% of RF power reflections when it appears at the antenna straps. In order to protect the transmitters, the whole transmitter system would shut down completely via crowbar under these conditions. This forceful shutdown can lead to unwanted wear and tear on the high voltage DC power supply system and impact the plasma operation due to the RF power interruption.

In order to enable the transmitter to "ride" through the ELM induced high power reflections and avoid unwanted crowbar conditions, we can modify the transmitter power control and protective circuitry to accommodate the ELM's perturbations.

I. INTRODUCTION

Through developments made by the broadcast industry, high power transmitters between 10 MHz and 100 MHz can be obtained at a reasonable price[1]. Thus, the ion cyclotron and harmonics fast wave heating in this frequency range for magnetic fusion energy research becomes very attractive. At present, two sets of 2-MW ABB transmitter tuned at 90 MHz are used for this purpose on DIII-D fusion facilities (General Atomics, San Diego, CA)[2][3]. However, the plasma loading conditions are not constant during the operation. Especially during the edge localized mode (ELM), we have observed that greater than 90% of RF power was reflected when it appears at the antenna straps. In order to protect the transmitters, the transmitter system will shut down completely through crowbar under this circumstance. Typically, this forceful shutdown not only stresses its power supply system but also impacts the plasma operation due to its long restarting time.

Since the duration of the ELM lasts in sub-milliseconds range and can be distinguished from the system arcs (typically in micro-seconds range), we can modify the transmitter power control and alarm circuitry to accommodate the ELM situation and avoid the system crowbar.

In this paper, the 2-MW ABB transmitter control and protective circuitry will be described to understand the possible approach for resolving this issue. Then the proposed circuitry and its functional blocks will be described in details. Finally, this paper will discuss where to insert this proposed circuitry and how this circuitry will interact with the control and protective circuitry to dynamically control the transmitter output power during the ELM situation

II. ABB CONTROL AND PROTECTIVE SYSTEM

The 2-MW ABB transmitter (Fig. 1) consists of a PIN attenuator, a Mini-Circuit ZFL-500 solid-state amplifier, a Tomco intermediate power amplifier (IPA), a 4CW150000 driver amplifier (DR), and a 4CM2500KG final power amplifier (FPA). There are filters and matching networks that are placed between those amplifiers. In order to monitor the system performance for different output power levels, two sets of directional couplers are placed in the system. One set is at the output of DR to monitor the DR output power as well as the matching between DR and FPA. Another set is at the output of FPA to monitor the output power as well as the matching between FPA and Antenna[4]. This FPA output power monitor also provides the reference to the feedback network for regulating the output power level.
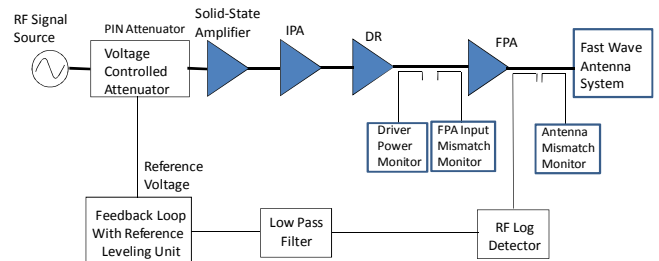

Fig. 1. A simplified diagram to represent the 2-MW ABB transmitter and its power contro feedback loop.

A. ABB Power Control Circuitry

The simplified power control network is shown in Fig. 1. As the final output power is sampled by a calibrated directional coupler, it is fed into an RF Log Detector. The output of the detector is a slowly varying voltage signal corresponding directly to the RF power level. Since the

signal contains RF and power supply noise, a low pass filter is used to remove those noises.

Then, this voltage signal, *Vin,* is compared with the preset voltage level V_S, which corresponds to the desired RF output power determined by *R4* pot, as shown in Fig 2. In reality, this *R4* pot is a complicated RF power control and display network. When *Vin* is low initially, the comparator output is at V$_+$ and the reference voltage *Vout* is adjusted to be 0 V through *R6* pot. Thus the voltage at the integrator input is about $V_D \simeq 0.8$ V. As soon as *Vin* (output RF power level) is greater than V_S, the output of the comparator will be pull down to the ground level and the capacitor *C* will be charged through the integrator by $V_D/R5$. The slew rate, $V_D/(R5C)$, is determined by *R5* pot and *Vout=V_D [t/(R5C)-1]*, where *t* is the time after the comparator changes its state. This *Vout* will force the PIN attenuator to increase the RF attenuation until *Vin* drops below V_S. This will pull up the output of the comparator and reverse the storage charges in *C. Vout* as well as the attenuation of the PIN attenuator will be reduced under this condition. This will lead to more RF power at the output and raise *Vin* above V_S again. The slew rate at this time is (V$_+$-V_D)/[(R7+R5)C]. If there is no change on V_S (fixed RF output power), *Vout* will remain quasi-constant with small fluctuations (steady state) even though the comparator output will be flip-flopping between high and low levels much faster than these two input slew rates. The typical output waveforms for this operation are shown in Fig. 3.
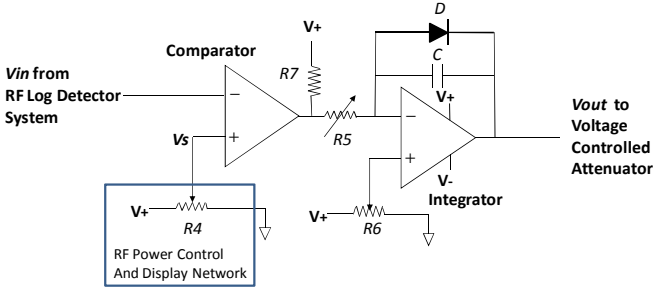

Fig. 2. The reference leveling unit consists of a comparator and an integrator; *R4* pot in reality is a complicated network that is used for RF power control and display.
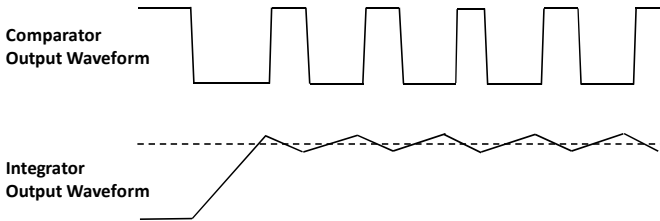

Fig. 3. Typical output waveforms for comparator and integrator in the reference leveling unit. In steady state, the integrator output is a quasi-constant with small fluctuations.

B. ABB Protective System

In order to protect the system, ABB designed the meter boards with the alarm/shut down circuitry to monitor DR screen and plate current, FPA grid, screen, and plate current, as well as DR and FPA reflected power. DR reflected power

is due to the FPA input mismatch and FPA reflected power is due to the Antenna mismatch. The basic circuit is shown in Fig. 4. R3 pot in the circuit is to calibrate the meter indicator for full swing at the maximum value. R4 pot is used to set the alarm/shut down level during the operation. Under normal conditions, meter voltage $|V_m|$ is less than alarm voltage $|V_a|$ and the comparator output is at V$_+$. This would force the capacitor *C* to be charged up to V$_+$– V_a through R2, R3, and R5. Diodes D1 and D2 are reversed biased at this time. As soon as an alarm condition occurs, $|V_m|$ becomes higher than $|V_a|$. The output of the comparator will be pulled down to reference level (0 V) and both diodes will become forward biased. This will force the alarm/shut down voltage at the comparator input dropping down to $V_a + V_D - V_+$ and then will slowly swing back to V_a with the time constant R5C$\simeq$0.5 ms. During this period, the comparator output will be locked at 0 V for ~1.5 ms. Since $V_a + V_D - V_+$ is far below $|V_m|$, it is almost impossible to reverse the output of the comparator no matter how fast V_m changes back to normal and thus the Alarm/Shut Down Circuitry is triggered through D2. In this case, the only method to restart the system is to clear the alarm. Usually, the capacitor will be fully discharged during the shut-down. If it is not, the maximum alarm/shut down voltage will initially be V$_+$+V_a and then slowly swing back to V_a with the time constant (R2+R3+R5)C. The alarm/shut down waveform at the comparator threshold input is shown in Fig. 5.

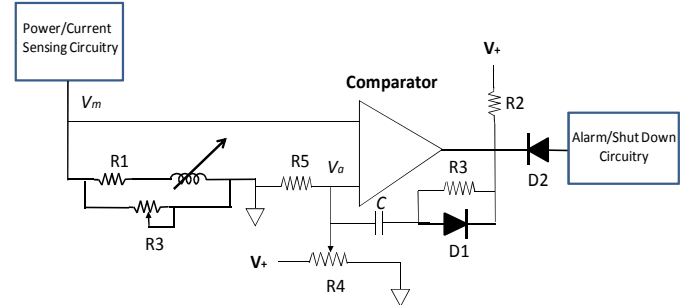Fig. 4. Circuit diagram for the ABB transmitter meter board with the alarm trigger circuitry. R4 is used for setting the alarm threshold and the comparator output is at V$_+$ during the normal operation.
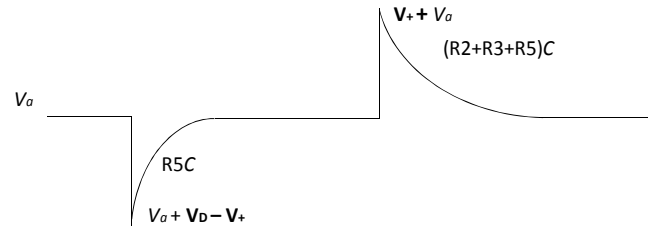

Fig. 5. Typical comparator threshold input waveform when the comparator is alternating its state from V$_+$ to 0 V.

III. MODIFICATIONS CIRCUIT DESIGN

After understanding the ABB transmitter power control and alarm/protective system, we can use the signals at the meter boards and affix a simple circuitry to inject the

correction signals into the power control circuitry upon ELM's appearing at the antenna straps during the plasma operation. There are two parts in this simple circuitry. The front end part is the RF amplifier sensing circuitry. The second part is the RF power controlling circuitry.

A. RF Amplifier Sensing Circuitry

As shown in Fig. 6, the key components of this RF amplifier sensing circuitry are a comparator and a diode[5]. Since we can reuse the signals V_m delivering to the meter boards, we do not have to design any new power/current sensing circuitry or add new sensors to the amplifier system.

During the normal operation, the comparator output is always high at V_+ and the diode is reverse biased. V_s, which can be adjusted by R4 pot, should be less than the alarm/shut down threshold. The optimal V_s value can be determined by trial and error during the plasma operation. As soon as $|V_m| > |V_s|$, the output of the comparator will be pulled down to reference level (0 V) and the diode will become forward biased to trigger the RF power controlling circuitry.
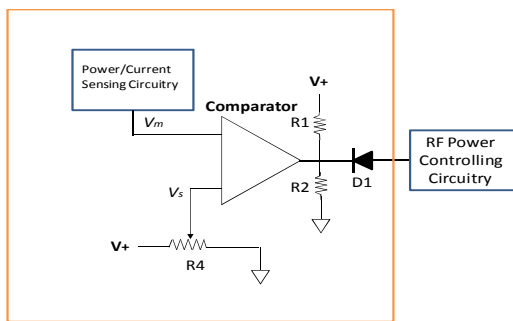

Fig. 6. RF amplifier sensing circuit diagram, the comparator output should be at V_+ and V_s should be less than the alarm/shut down threshold under normal operation.

Note that there is more than one sensing circuitry in the system in order to monitor different parameters during the operation. Diode D1 in this case functions like a NOR gate to join all the sensing circuitries and to prevent any cross-interference among them.

B. RF Power Controlling Circuitry

As shown in Fig. 7, the RF power controlling circuitry, which applies the same design concept for the ABB power control circuitry, is an integrator with a low pass filter. Since all the sensing circuitries are at V_+ under normal operation conditions, diodes D1 and D2 will be forward biased. The output voltage V1 will be adjusted to be zero through R4 pot and the voltage $V_r = 2V_D \simeq 1.6$ V. If one or more sensing circuitries reverse the state, the input voltage at R1 will become V_D due to the diode in the sensing circuit. Thus capacitor C1 will be charged through R1 with the slew rate $V_D/(R1C1)$ and the output voltage will become $V1 = V_D t/(R1C1)$, where t is the time after the sensing circuitry changes its state. R2 and C2 form a low pass filter to remove any spikes when any comparator is switching the state.

This V1 is combined with the reference voltage or preset voltage in the ABB power control circuitry as a small

correction voltage. Since the duration of the ELM is in sub-milliseconds range and can be distinguished from the system arcs (typically in micro-seconds range), R1 pot should be adjusted to keep the R1C1 time constant to be in tens of micro-seconds range. Hence, if there is an arc, the ABB transmitter will shut down itself; but if there is an ELM at the antenna straps, V1 will immediately reduce the RF output power and bring the system back to normal operation instead of shutting down. As soon as the system is back to normal, all comparator outputs in the sensing circuitry will become V_+ and C1 will be charged reversely to return to V_r. The slew rate at this time is $(V_+ - 2V_D)/[(R3+R1)C1]$. The typical output waveforms for this operation are shown in Fig. 8[6][7].
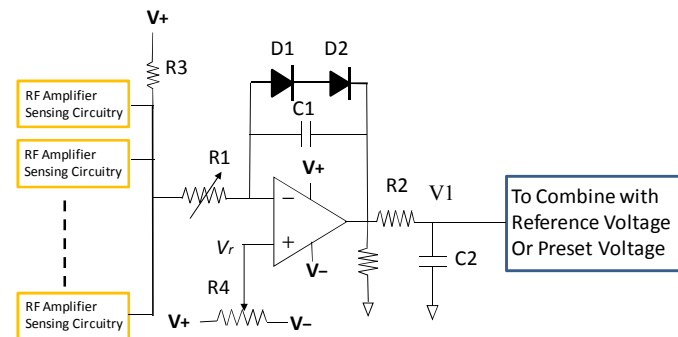

Fig. 7. RF power controlling circuit diagram; diodes D1 and D2 are forward biased and the output voltage V1 is adjusted to be zero through R4 and the voltage $V_r = 2V_D \simeq 1.6$ V under normal conditions.
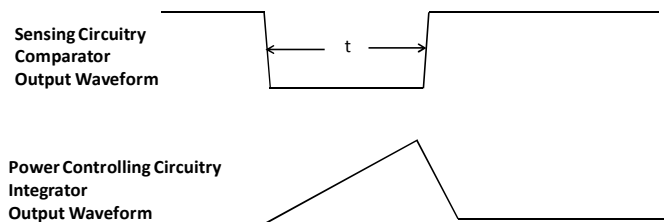

Fig. 8. Typical output waveforms when one or more sensing circuitries exceed the threshold; the slew rate in this case is $V_D/(R1C1)$ and $V1 = V_D t/(R1C1)$ when the comparator output is low; the slew rate becomes $(V_+ - 2V_D)/[(R3+R1)C1]$ when the integrator output becomes high again.

C. Combiner and System Performance

There are two methods to combine this power correction voltage V1. One is to reduce the preset voltage level V_S in reference leveling unit. Another is to increase the reference voltage to the voltage controlled attenuator. In other words, the combiner can be a simple analog adder or substractor formed with few operational amplifiers[6].

The first method is shown in Fig. 9. As shown in the figure, V1 is connected to the negative input of a substractor formed with 4 R's. The ABB preset voltage level V_S passes through a buffer first to reduce any undesired interaction from this addendum circuitry. Then it is connected to the positive input of the substractor in order to obtain $V_S -$ V1 and thus reduce the RF output power. R5 and C3 form a low pass filter to increase the noise immunity of the whole system and D1 is to prevent any spikes that might back feed

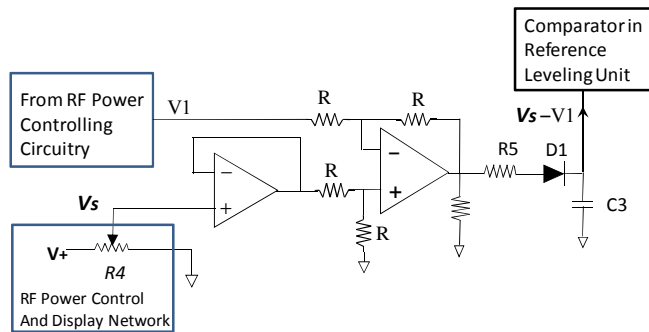from the RF attenuator and other circuits to impact the system performance.

Fig. 9. An analog substractor is used to obtain $V_S - V1$, thus this power correction voltage V1 will reduce the RF output power accordingly.

The second method is shown in Fig. 10. In order to increase the voltage at the attenuator for reducing the RF power, voltage V1 first passes through an inverter formed with two R3's and then to the negative input of a substractor as discussed previously. The ABB power control voltage *Vout* will pass through a buffer first to reduce any undesired interaction from this addendum circuitry. Then it will be connected to the positive input of the substractor. This results in the voltage at the attenuator input to be *Vout* +V1 and then lowering the RF output power. The same low pass filter and diode are used to increase the noise immunity and to prevent any spikes that might impact the system performance.
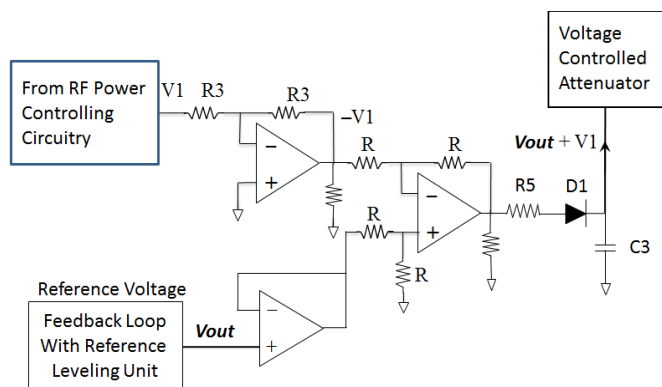

Fig. 10. An analog adder is used to obtain *Vout* + V1, thus this power correction voltage V1 will increase the attenuation and reduce the RF output power accordingly.

IV. CONCLUSIONS AND FUTURE WORK

Ion cyclotron and harmonics fast waves in tens of megahertz frequency range have been proved to be one of the useful methods to heat the plasma for magnetic fusion energy research. Two sets of 90 MHz 2-MW ABB transmitters located at General Atomics DIII-D facilities have been put in service to heat the fusion plasma for years. Nevertheless, the plasma loading conditions are not constant during this heating process. Especially when the ELM's appear at the antenna straps, they can cause up to 90% of RF power reflection and completely shut down the transmitter through crowbar. This forceful shutdown not only stresses

the transmitter power supply system but also impacts the plasma operation due to its long restarting time.

After understanding ABB transmitter power control scheme and its associated meter board functions, we have proposed a simple circuit design to modify the transmitter power control and alarm circuitry to accommodate the ELM situation. Hence it will not drastically shut down the system and simply interrupt the RF output via crowbar.

According to the experimental data, the duration of the ELM is in sub-milliseconds range and can be distinguished from the system arcs, which are in micro-seconds range. As discussed in Sec. III, we can directly use the signals at the meter boards. However, we need to know the levels of fluctuations and durations of those signals during the ELM conditions in order to determine the thresholds for the sensing circuitries and the slew rates for the integrator in the power controlling circuitry. This will require a lot of in situ testing to fine tune the system performance so that it can enable the transmitter to "ride" through the ELM's.

Two prototype circuit boards have been built. We will be able to install and test them after the systems are taken out of their mothball state determined by the present physics program. Hopefully, we will have the chance to test these two circuit boards during or after this period.

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