STABILITY TEST OF NEAR-MAGNET POWER AMPLIFIER

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Purpose

In our 7T MRI installation, a 32-channel pTX system with power amplifiers (PA) near the magnet presently is under construction. Due to the mutual coupling of the coils and with grossly non-uniform excitation, as often used in RF shimming [1], individual power amplifiers will experience high load reflection coefficients, potentially greater than 1 at phases of 0° to 360°. MRI safety requires unconditional stability of the PAs at any load. In conventional transmitter installations, this is provided by isolating the amplifiers from the coils using ferrite circulators / isolators. Since circulators must not be used because of high magnetic flux near the magnet, power amplifier stability becomes a critical issue to test. Here, we propose a bench stability test which employs an electronic circuit designed to realize reflection coefficients with variable magnitude and phase such that all possible combinations can be checked for instability in the power amplifier device under test (DUT). In addition the stability under high reverse power to the DUT output in measuring the large-signal reflection coefficient of the PA can also be tested.

Methods

In power amplifier engineering, the technique of generating variable loads ("Load-pull") is used to optimize matching impedances and output power of RF amplifiers [2,3]. In "active" load-pull circuits, the output power of the device under test (DUT) is absorbed in a circulator/load combination (isolator) and a sample is used to excite a second power amplifier to return a power signal through the circulator back to the DUT. By changing the amplitude and phase of the returned signal in an I/Q-modulator, the reflection coefficient can be controlled in a wide range between zero and even larger than 1. As the circulator for our operating frequency (298 MHz) is not easily available, we propose a modified load-pull circuit, which replaces the circulator by a directional coupler (Coupler 2), Fig.1. A first coupler is used in the circuit to sample either the forward (connection "F") traveling wave (representing the available output power) or the backward (connection "B") wave and to create signal ratios between port 1 and port 2 using the Vector Network Analyzer (VNA). The output power of the load-pull PA has to be equal or greater than the DUT to be able to produce reflection coefficients of 1 or more. In our circuit, the same 1kW PA design [4]as the DUT is used as the load-pull PA. However, as the output impedance of the load-pull PA is mismatched, the output is buffered by a 6 dB attenuator to improve the match and reduce its "passive" reflection coefficient when the I/Q modulator is set to zero. The coupler used to couple the DUT signal to the I/Q modulator must have high directivity to prevent instability of the load-pull circuit itself. Here, a λ/2 directional coupler is used to get 25 dB directivity at -20 dB of coupling. The I/Q modulator includes a quadrature power divider, balanced mixers and power combiner; the in-phase and quadrature control voltages are generated under computer control to create any desired reflection coefficient. In our setup, the control voltages can sweep the reflection coefficient over a circular constellation in the complex plane with variable magnitude in order to cover all possible states. Both amplifiers,the VNA and the monitor oscilloscope operate in lowduty-cycle pulse mode triggered by a pulse generator not shown in the schematics.

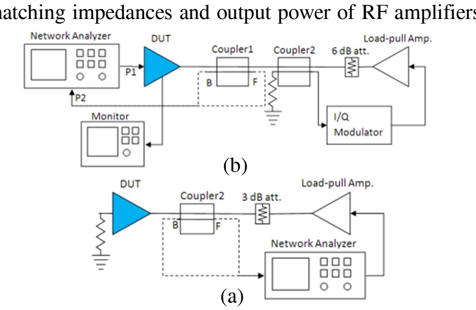

Fig.1Proposed structure of the test circuit, Set-up for Load-Pull (a) and for large-signal S_{22} (b)

Measurements

Two load-pull test cases are presented in Fig.2 for 50 W and 400 W output power of the DUT for high and low excitation respectively, and with maximum control voltages at the I/Q modulator while rotating the phase of the load-pull return signal between 0° to 360°. It can be seen in Fig.2(b) that as the control voltages are swept, the reflection coefficients are also sweeping over a closed loop across the complex plane. At the same time, Fig.2(a) shows that the forward wave from the DUT varies in amplitude and phase due to the variation in the reflection coefficient. It is also seen that it is easy to realize a large reflection coefficient at low DUT power while at high DUT power the load-pull amplifier could not provide the high power level for the return signal such that the reflection coefficient remains small. In both cases, the centers of the closed loop reflection coefficient traces are shifted due to the residual mismatch of the load-pull amplifier. Using the modified set-up of Fig.1(b), tests extended to the measurement of the large-signal reflection coefficient (S_{22}) of the DUT as function of the reverse power while at the same time the DUT output was monitored for any indications of instability. Fig.3 shows that the large-signal reflection coefficient of the DUT is quite stable over reverse power level.

Discussion

The most critical situation w.r.t. instability of linear power amplifiers usually is the small-signal situation while large-signal / high power excitation is less prone to instability due to saturation effects. Therefore, the load-pull test at 50 W was repeated with variation of the reflection coefficient between 0 up to slightly above 1. No instabilities were discovered by observation of the monitor oscilloscope during the tests. For larger reflection coefficients at high power, the attenuator buffering the load-pull amplifier would have to be removed. However, in this case the offset of the reflection coefficient loop center would increase with some unreachable area in the complex plane; this could only be corrected by using a ferrite circulator / isolator or using a hybrid to combine two equal PA's as the load-pull amplifier. A special case of instability test is established by the pure reverse power excitation while the DUT is terminated at its input. In both series of tests, the DUT was found perfectly stable.

Conclusion

Using the proposed load-pull structure, the variation of the load in an MRI environment was simulated to test an RF amplifier for instability problems. The set-up also showed the variation of forward wave amplitude and phase dependence on the load reflection coefficient, which would degrade MRI performance and which requires feed-back control to overcome. Results show that the RF amplifier is unconditionally stable, since no oscillations are seen in any tested mismatch situation (small and large reflection coefficient with any phase). The measured large-signal reflection coefficient of the DUT indicates high impedance even at several 100W reverse power. With suitable phase adjustment, this canbe used to realize amplifier decoupling of the coils. Apart from stability, it is notable that the power amplifier did not fail even under full power and total reflection (open-circuit and short-circuit) which is due to the latest advances in ruggedized LDMOS transistors for RF applications.

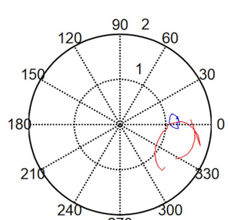

Fig.2(a): Normalized representation of the forward wave signal for 50 W (red) and 400 W (blue) DUT output power

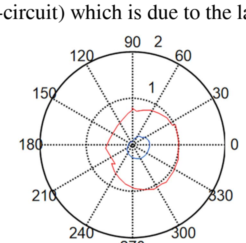

Fig.2(b): Reflection coefficients (ratio of backward and forward wave) for 50 W (red) and 400 W (blue) DUT output power

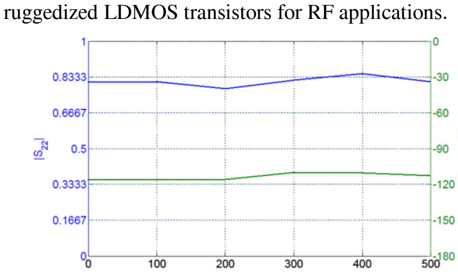

Fig.3: large-signal reflection coefficient (S_{22}) for different revers powers

References: [1] YazdanbakhshP. et al.: Variable Power Combiner for the RF Mode Shimming in 7-T MR Imaging, IEEE Trans. Biomed. Eng., vol. 59, no. 9, Sept. 2012, 2549-2557, [2] Ghannouchi F.M., Hashmi M.S., Springer Series in Advanced Microelectronics, 2013. 978-94-007-4460-8, [3] Bava G.P. et al, Electronic Letters, 1982 Vol. 18 No. 4, 178 – 180, [4] Solbach K et al.: Near-Magnet Power Amplifier with Coil Current Sensing, submitted ISMRM 2014

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