

High power Constant Current Class EF2 GaN Power Amplifier for AirFuel Magnetic Resonance Wire-less Power Transfer Systems

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Abstract

This paper presents the constant current Class EF2 power amplifier (PA) for magnetic resonance WPT with GaN devices, where the current output of the Class EF2 PA remains almost constant when the load impedance varies. The solution enables power transfer coil load of the WPT system to simultaneously support multiple devices and naturally supply the power demanded by receiver with open loop. The design methodology of Class EF2 PA will be discussed in detail, followed as a customer solution design for WPT. The Class EF2 PA can deliver 150W CW power at 6.78MHz, with 94% efficiency at 70V before EMI filter.

1.Introduction

Magnetic resonance based wireless power transfer technologies emerged in recent years, leveraging its loosely coupled nature and higher operating frequency (6.78MHz), it is able to offer differentiation in position flexibility, separation distance, charging cross metal cover and multi-device charging, over inductive solutions (i.e. Qi). Especially for the support of multi-device charging, as shown in Fig1,

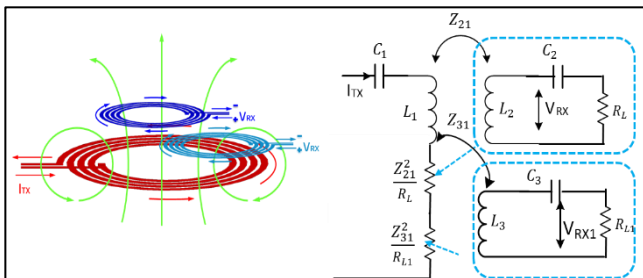


Fig. 1. (a) Multiple device charging configuration. (b) equivalent circuit model when the transmitter and receiver coils are series tuned, the load of the receivers are transformed to the transmitter as series resistance at primary

side through mutual coupler inversely proportional to the load resistance value. [1]

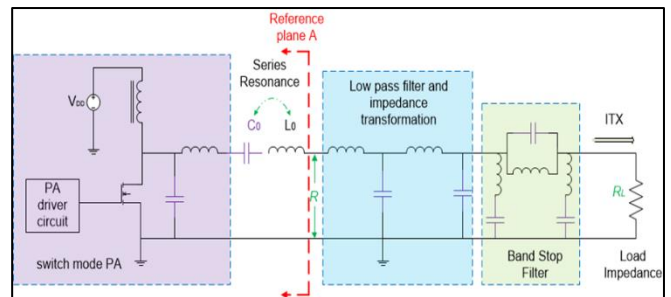


Fig. 2. Class E constant current PA to drive TX Coil

In wireless charging system, the PA load naturally is a coil with low impedance. In this case, if PA operates in voltage mode, it would draw a very high drain current under light load condition. if a PA operates in constant current mode, not only the devices of PA can operate in low current under light load condition, but also it would allow multiple receiver devices to get the power it demands naturally from the transmitter and independent of each other [1].

Fig.2 depicts the Class E PA topology to generate constant current output to varying load, which optimized for magnetic resonance wireless power systems using switch mode PA to provide constant RF current to varying load. Air Fuel compliant, regulatory approved PA solution [1].

In this paper, we propose another new type of PA topologies, Class EF2, which also implements switch mode PA to provide constant RF current to varying load, Air Fuel compliant, particularly for higher power application, such as plasma generator.

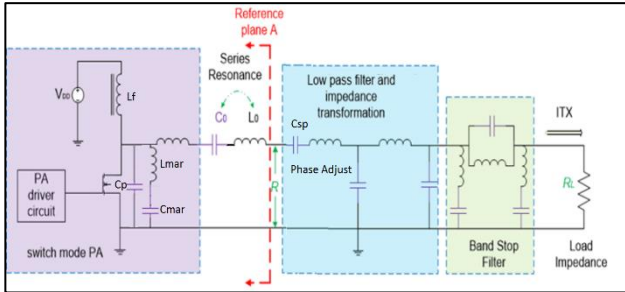


Fig. 3. Circuit diagram of the Class EF2 constant current PA topology

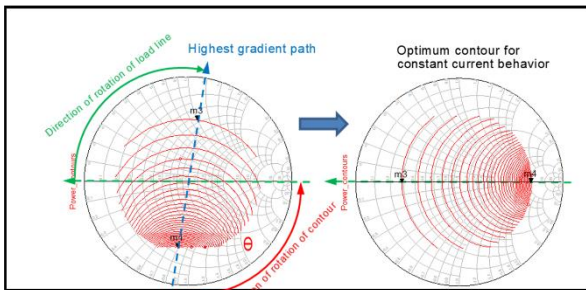


Fig.4. (a) Constant power contour (at plane A), load line of a typical Class EF2 switch mode PA

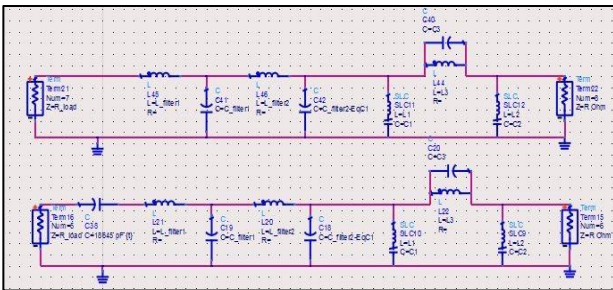


Fig. 5a. Class E network in [1] (up), Class EF2 network in this work (down)

2. Class EF2 Constant Current PA Design

This paper proposes a Class EF2 switch mode constant current PA topology, which could be designed as a ground-referenced switch, and relatively low voltage stress on the devices. Therefore, the PA can operate at higher supply voltage with lower current to gain more efficiency.

The advantage of Class EF2 PA compares to Class E PA [3] lies overall performance, and can

stands on higher output power level. One series matching capacitor provides a feasibility of flexible devices in the constant current impedance conversion network.

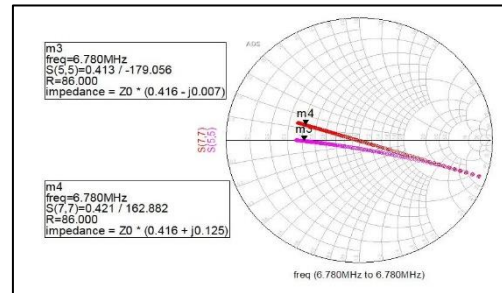


Fig. 6. (a) Red line tank impedance Class E [1] (b) Magenta line tank impedance pre-match with Csp in Fig.3

The general block diagram of the proposed constant current PA design is shown in Fig. 3, where the system is consisted of 3 sub-circuits— (1) switch mode PA with L-C shunt, (2) Low pass/band pass filter and impedance transformation with Csp and (3) band stop/notch filter.

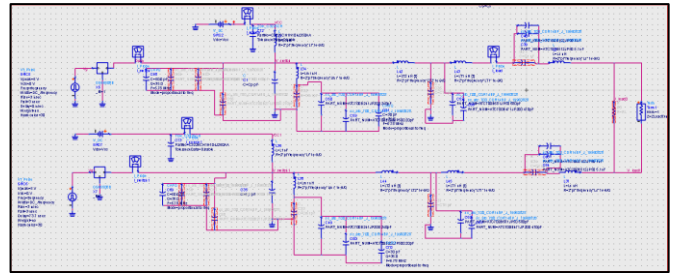


Fig.7. Switch mode PA push-pull Class EF2 with GS6650B8B

All impedance transformation and filter network introduce phase shifts which alters the output behavior of the PA. Fig. 4(a) depicts the constant power contour of a typical Class EF2 PA with infinite inductance plotted with center of smith chart at R. As that can be seen, the constant power contour intercepts the real axis with multiple contour lines, which indicates that the output power first increase and then decreases as the load impedance increases.

For the best constant current behavior, as shown in Fig. 4(a), the load line of increasing load resistance need to be rotated from the real axis of smith chart to align with the path of maximum gradient of the constant power contour of the switch mode PA.

For Class EF2, PA targets high power application, the switching devices are high voltage along with bigger die and package size. In most case, the

output inductance is much bigger from combination of the multiple dies inside package.

The tank impedance is inductance at reference plane A in Fig.3 mostly. The high inductance affects phase of impedance conversion network, which can't convert the impedance in place. One capacitor series in the output pre-match impedance to point lose real axis, which place important role in high power Class EF2 PA design. Red line is without Csp, magenta line is with Csp in Class EF2 in Fig.5

Smith Chart. And in conventional Class EF2 PA, C0 does not play any impedance role, just as a DC blocker [4]. In this work, C0 combines Csp, and involves impedance matching in output.

3. High power Class EF2 PA Design

The GaN systems 650V GaN devices GS66508B are employed in this Class EF2 design with push-pull configuration, the targeted optimized impedance is 50 Ohm. The peak efficiency is 94% at 150W output power. GaN systems offers a wide portfolio of GaN technology for fast switching application, and penetrating the high frequency and power application such as WPT, plasma generator. A push-pull Class EF2 topology is designed as shown in Fig. 7 with 60V supply voltage.

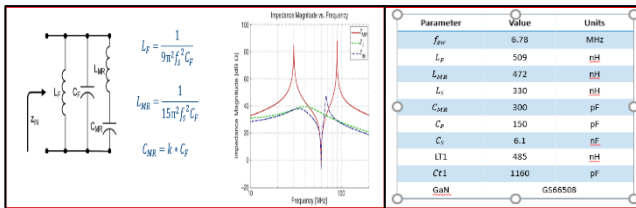


Fig.8. (a) Class EF2 tank component values equations [3,4]. (b) impedance performance of the tank of Class EF2 PA (c) Detailed values of PA design

The wireless power coil system requires the PA to provide 200 Watts to a 30Ohm load. Based on the design equation for for Class EF2 PA of this topology [2,3], the L and C values can be calculated as shown in Fig.8.

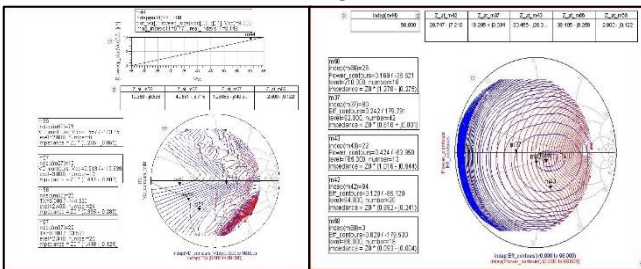


Fig. 9. (a) Simulated output current contours vs. Air Fuel certification required impedance range, (b)

Simulated constant power and efficiency contours as constant current mode

The load pull simulation of this PA structure is carried out and results of voltage mode at reference plane A is shown in Fig.9 (b), where the peak efficiency is 96.6% with 200W CW power. The Csp pre-matches the impedance, the real axis aligns with the path of maximum gradient of the constant power contour of the switch mode PA at reference plane A.



Fig.10. 150W Air Fuel high power PA close up view

Fig. 9 (a) shows the simulated load pull contours after impedance conversion network at load of PA in constant current mode. The PA design outputs desired power at the target impedance. 94% efficiency with 210W at 29.5 ohm. And also demonstrates a nature constant current PA performance, low output power at low impedance (marker M68, 15W at 2.6 Ohm, marker M66, 210W at 38 ohm). That is perfect fit the nature load of WPT coil load. The output current variation is from 2.34 to 2.4 A (marker M67 to maker M56)

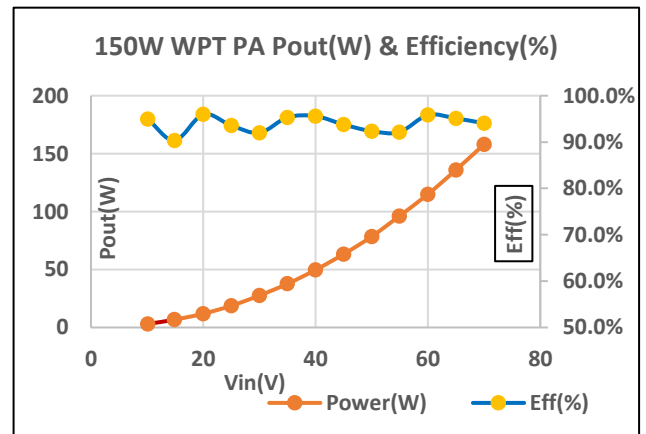


Fig.11. 150W High power PA measurement data

Fig. 9 (b) depicts the constant current contours at the output of the filter and the required impedance range for constant current behavior based on Air Fuel specification. where the current variation in the impedance range is between 2.34A and 2.4A. The PA design is implemented in a wireless charging system prototype as shown in Fig.10. The EMI notch filter is integrated in PA design [1]. Fig.11 depicts the measured results. The peak

efficiency is 95%, and output power at 50ohm load is 184W at 75V input voltage with 94% efficiency. The measurement data is taken at 500W 50ohm load.

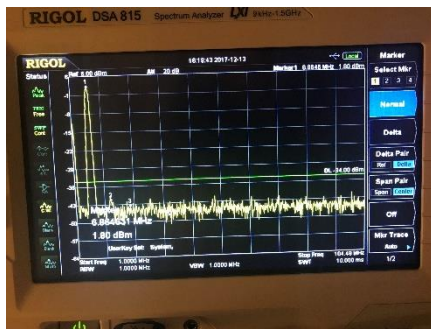


Fig.12. Harmonics cross 1-200mHz at 150W output power after EMI filter (with 49.66dB attenuation)

For the higher than 2nd harmonics, the rejection is better than -53dBc. The 2nd harmonic is around -48dBc.

4. Conclusion

A new type Class EF2 of power amplifier catered to magnetic resonance wireless power transfer

application with GaN systems devices is introduced, where the output network of a Class EF2 PA is synthesized to perform low devices stress as well as providing the phase shift PA needed to put out near constant output current over wide range of load with high efficiency and high power. The efficiency PA with GaN devices is overall higher 5% than other technologies.

References

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- [3] Juan M. Rivas, Yehui Han, Olivia Leitermann Anthony D. Sagneri and David J. Perreault, "A high-frequency resonant invert topology with low voltage stress" IEEE Transactions on Power electronics, VOL.23. NO.4,July 2008