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Four-switch Class-PN Power Amplifier for High Power Handling Capability in Wireless Power Transfer

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***Abstract*—Most power amplifiers (PA) for wireless power transfer (WPT) are based on single switch topologies (Class-E, F, Φ,). Single-switch topologies are easy to design and operate, but they are limited in power handling capability. Utilizing multi-switch topologies increases device utilization which improves power handling capability. In this paper a novel topology is introduced, which is referred as Class-PN. Class-PN is based on four switches, and is shown to have more than 6x higher power handling capability than Class-E. The topology consists of no resonating passive components, thus the same PA is operational at multiple switching frequencies. Series resonating load at output power of 135W and switching frequency of both 7MHz and 12MHz are shown at first to verify operation of Class-PN power amplifier. Finally, inductively coupled coils are used to transfer power wirelessly between the transmission and receiving coil. Wireless power delivered to the load at 6.15MHz of switching frequency is 400W, which was limited by the radio frequency (RF) load.**

***Keywords*—Inductive power link, RF converters, Wireless power transfer, ZVS converters.**

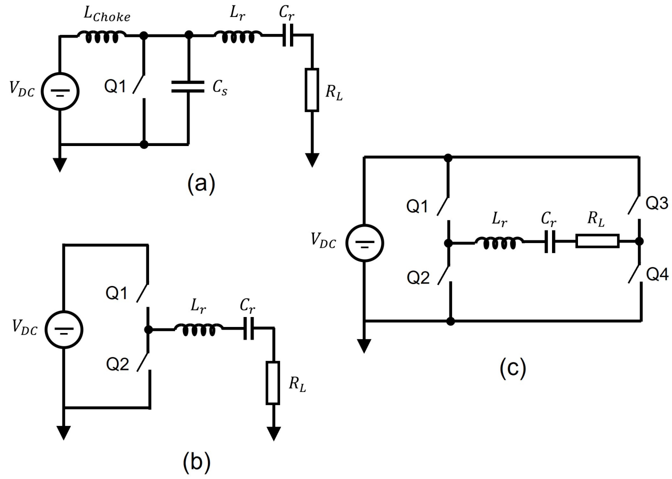

Fig. 1. (a) Class-E topology, (b) Class-D topology, and (c) Full-Bridge topology.

I. Introduction

Wireless power transfer has been gaining traction, owing to its ease of use replacing charging cables. In coming decades a standard home is expected to be retrofitted with wireless charging stations. For example wireless charging for personal appliances and electric vehicles (EV). These varied applications will require power from few 100's W to few 10 kW for EV charging.

Today most WPT technology is based on resonant converter topology with a single switch like Class-E, Class-F, Class-Φ [1], [2], [3]. The argument behind single switch topology is that PA for WPT are usually required to operate at several MHz of switching frequency, thus the time period is less than 100ns for above 10MHz. In such scenario multi-switch topology like Class-D or Full-Bridge (FB) need to operate safely with minimal deadtime of possibly 10ns to avoid shoot-through. Therefore most work on resonating converters utilizing Class-D or FB operate at sub-MHz frequency [4], [5]. Fig. 1 shows three topologies with different switch count. All the three topologies are shown with series resonant load. Another point to observe is that the load (R_{L}) in FB is floating as compared to Class-E or Class-D where the load can be properly grounded.

Though a single switch topology is easier to design and operate but the switch is subjected to high voltage and current stress. High voltage and current stress on switch, limits device utilization which results in limited power handling capability. In Sec. II power handling capability is discussed and its significance is presented in terms of a few topologies. In Sec. III Class-PN is introduced and its power handling capability is derived. The section also provides a summarised list of other single and multi-switch topologies power handling capability. In Sec. IV preliminary results for the Class-PN for a series resonating load are presented. Finally in Sec. V an inductive power link for WPT load model is introduced and experimental results are presented with Class-PN power amplifier.

II. Power handling capability

To serve high power requirement of future homes, high power handling capability is desired from power amplifiers. Power handling capability or normalized power handling capability can be used as a figure of merit (FOM) to evaluate a topology [6]. It utilizes the ratio of maximum voltage subjected to semiconductor switch drain-source (V_{SM}) to the DC link voltage (V_{DC}), as well as peak current through the switch (I_{SM}) ratio to the DC current (I_{DC}). Lower value of power handling capability

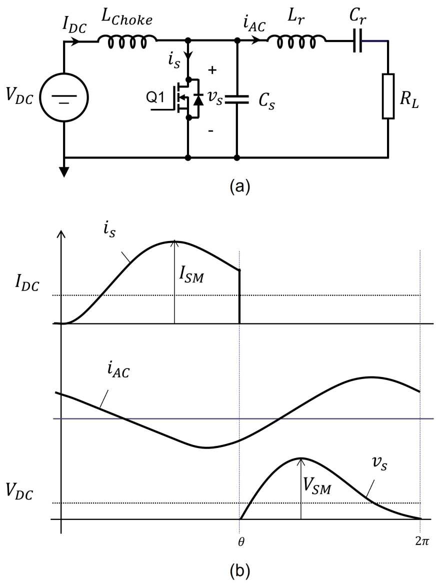

Fig. 2. (a) Class-E topology, and (b) Voltage and current through switch in Class-E and load current.

(C_{P}) means worse device utilization. In mathematical terms it is shown as (1),

$$C_{\mathrm{P}} = \frac{V_{\mathrm{DC}} \cdot I_{\mathrm{DC}}}{V_{\mathrm{SM}} \cdot I_{\mathrm{SM}}} \tag{1}$$

For example, Class-E is a popular single switch topology. But the topology subjects 3.6x the DC link voltage and 2.86x the choke inductor (L_{choke}) current on its semiconductor switch [6]. Voltage and current waveform through the switch in Class-E is shown in Fig. 2. Applying 150V DC link voltage will induce 540V stress on the switch. If using 650V GaN HEMT, DC link voltage cannot be increased much beyond 150V. High voltage stress is further exacerbated by non-linear behavior of output capacitance of the semiconductor device. Usually the device output capacitance is not augmented with an external capacitance and thus the non-linear behavior of output capacitance can lead to even higher drain-source voltage, approximately 4.4x of DC link voltage [7].

In order to overcome high voltage stress and yet retain the simplicity of single-switch topology, several other derivatives of Class-E have been proposed. Such as Class-F, and its derivative Class-Φ are some of the prominent ones. Class-Φ has only 2x DC link voltage subjected to the semiconductor switch. But this topology utilizes quarter wavelength ($\lambda/4$) transmission-line network to replace the bulky L_{choke} of Class-E [3]. This high-order resonant structure with multiple resonant passive components increase design complexity.

By reducing peak voltage stress, Class-E derivatives have been successful in improving power handling capability. Yet, two switch topology like Class-D perform almost twice as better. And four-switch topology like FB improves that by another factor of 2. Work done in this paper is based on a novel four-switch topology called Class-PN [8]. This four-switch Class-PN topology achieves the same power handling capability as FB. But in FB the load (R_{L}) is left floating as shown in Fig. 1(c). The structure of Class-PN on the other hand allows to ground the load (R_{L}) as shown in Fig. 3(a) analogous to other topologies like Class-E, F, and Φ. This is why we have referred to this topology as ”Class-PN”.

III. Class-PN Topology

In this work a novel four-switch topology is introduced as an RF power amplifier. The voltage and current waveform for the topology is shown in Fig. 3(b).

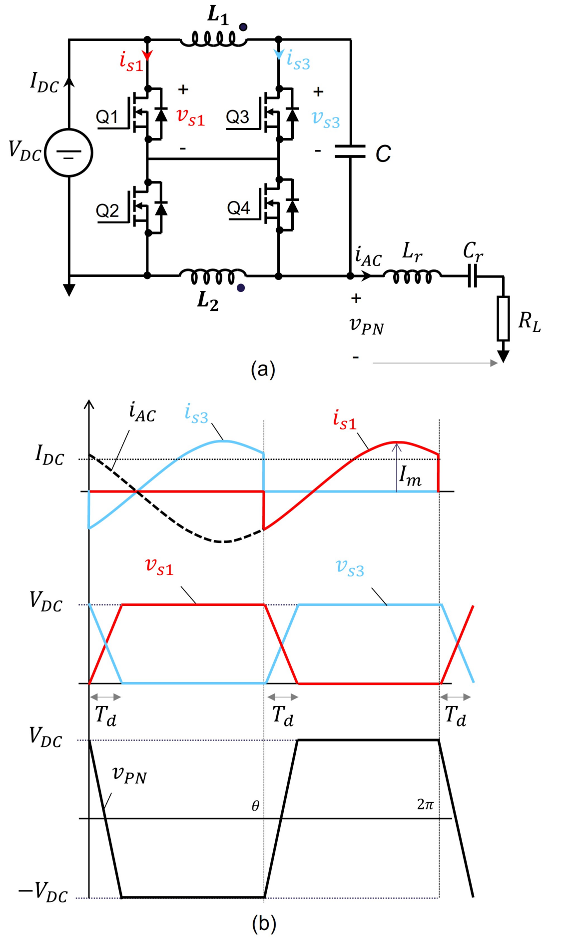

Fig. 3. (a) Class-PN topology, and (b) Voltage and current through switches and load current in a single period.

In Table I, Class-PN is shown to have power handling capability twice that of Class-D. This is due to the fact that in Class-D only half of the period is utilized to deliver power from DC link to RF load. To put this in mathematical terms, output voltage and current of Class-PN which is applied on the resonating load is given by (2),

$$\begin{aligned} v_{\mathrm{PN}} &= \begin{cases} V_{\mathrm{DC}} & \in \quad (0, \pi] \\ -V_{\mathrm{DC}} & \in \quad (\pi, 2\pi] \end{cases} \\ i_{\mathrm{AC}} &= I_{\mathrm{m}} sin(\omega t - \psi) \qquad \in \quad (0, 2\pi] \end{aligned} \tag{2}$$

TABLE I. POWER HANDLING CAPABILITY

Topology	Switch Count	V_{SM}/V_{DC}	I_{SM}/I_{DC}	C_P
Class-E	1	3.6	2.86	0.0981
Class-F	1	2	π	$1/2\pi$ = 0.16
Class-Φ	1	2	π	$1/2\pi$ = 0.16
Class-D	2	1	π	$1/\pi$ = 0.318
Class-PN, FB	4	1	$\pi/2$	$2/\pi$ = 0.636

Output voltage is a dual-pole voltage application (Positive and Negative) on the resonant load. ψ is phase angle due to load. Current flow from the devices can be expressed as (3),

$$i_{\mathrm{S1}} = i_{\mathrm{S4}} = \begin{cases} I_{\mathrm{m}} sin(\omega t - \psi) & \in \quad (0, \pi] \\ 0 & \in \quad (\pi, 2\pi] \end{cases}$$
$$i_{\mathrm{S2}} = i_{\mathrm{S3}} = \begin{cases} 0 & \in \quad (0, \pi] \\ -I_{\mathrm{m}} sin(\omega t - \psi) & \in \quad (\pi, 2\pi] \end{cases} \tag{3}$$

By combining current through the switches, DC input current from the DC link can be acquired as (4),

$$I_{\mathrm{DC}} = \frac{1}{\pi}\int_0^{\pi} I_{\mathrm{m}} sin(\omega t - \psi)\, \mathrm{d}(\omega t) = \frac{2I_{\mathrm{m}} cos(\psi)}{\pi} \tag{4}$$

At natural frequency (f_0) of resonant load, maximum DC link current is obtained (5),

$$I_{\mathrm{DC}} = \frac{2I_{\mathrm{m}}}{\pi}, \quad \text{at} \quad f_{\mathrm{sw}} = f_0 = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{5}$$

Thus, maximum current and voltage stress seen by the devices in Class-PN is given by (6)

$$I_{\mathrm{SM}} = I_{\mathrm{m}} = I_{\mathrm{DC}}\frac{\pi}{2}, \qquad V_{\mathrm{SM}} = V_{\mathrm{DC}} \tag{6}$$

A summary of the maximum device voltage and current stress in different topology and their power handling capability is presented in Table I.

IV. Series Resonant Load Results

In order to test the Class-PN power amplifier, a series resonating load network is used as shown in the schematic in Fig. 3(a). Developed Class-PN power amplifier utilizes GaN Systems 650V HEMT devices (GS66506T) [9]. Isolated gate drivers with separate pull-up/down output type are used from Skyworks (Si8271AB-IS) [10]. Power supply for gate driver is provided by a 600V-9V isolated flyback circuit that is controlled by LT8316 from Analog Devices [11].

In Fig. 4 the experimental setup for series resonant load test is presented. It shows the Class-PN power amplifier and a series resonant load. The PA is connected to a single DC supply (V_{DC}). Input voltage for gate driver power flyback circuit is provided from the DC link

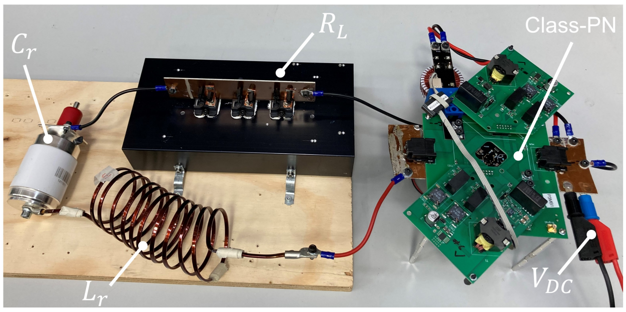

Fig. 4. Experimental setup containing Class-PN power amplifier and series resonant load.

voltage (V_{DC}) and capacitor (C) as a self-powering mechanism. The self-powering mechanism helps in reducing the number of external supplies required and was first presented in [12].

Unlike Class-E, F or Φ, this topology does not include any passive components to achieve soft-switching of semiconductor devices. Therefore Class-PN power amplifier can be operated at multiple frequencies. To validate, the PA is operated with series resonating load at both 7MHz and 12MHz of switching frequency (f_{sw}). Fig. 5(a) shows converter waveform for operation at 7MHz. The series resonating load is tuned for natural frequency (f_0) of 6.3MHz where the value of L_r, and C_r are 3.98μH and 161pF respectively. As shown in Fig. 4, the load inductor (L_r) is an air-core type while the load capacitor is a variable vacuum capacitor from COMET pct. Fig. 5(b) shows waveform at 12MHz of switching frequency (f_{sw}). In this case the value of L_r, and C_r are changed to 2.6μH and 84pF respectively which gives a load natural frequency (f_0) of 10.8MHz. Loads are tuned at the respective natural frequency so that the power amplifier operates in inductive region. When the load current is high enough it ensures that HEMT undergo soft-switching during the deadtime (T_d) [13]. Load resistance (R_{L}) in both cases is a parallel combination of three flat chip type RF resistors of 33Ω each resulting into 11Ω R_{L} value.

For both cases in Fig. 5 the DC link voltage is 200V. Class-PN output voltage (v_{PN}) shown here agrees with waveform presented in Fig. 3(b). Thus HEMT devices used in PA have voltage stress equal to DC link voltage, ensuring power handling capability of 0.636. Load current (i_{AC}) in both cases has a peak value of 5A, shown by dotted line in Fig. 5. Thus the PA is delivering 135W at both 7MHz and 12MHz of switching frequency (f_{sw}). Also in Fig. 5 load capacitor (C_r) voltage is provided.

V. Wireless Power Transfer Load Model and Results

In a WPT system, inductively coupled coils - transmitting coil and receiving coil are designed without a magnetizing core. Therefore coupling co-efficient (k) is very low, often between 0.3 - 0.5. Low coupling coefficient is usually compensated with capacitor to induce resonance. Both series and parallel resonating network can be used for transmission as well as receiver side

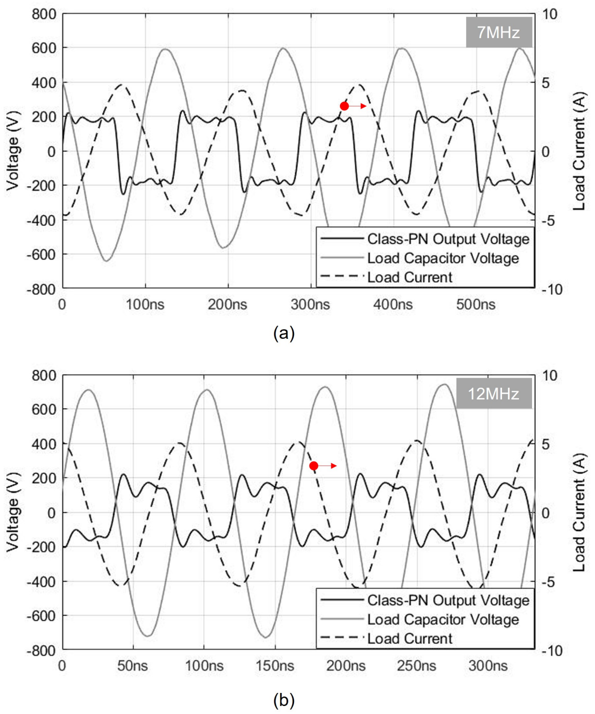

Fig. 5. Class-PN operation with series resonant load at different switching frequency, (a) 7MHz of switching frequency, (b) 12MHz of swicthing frequency.

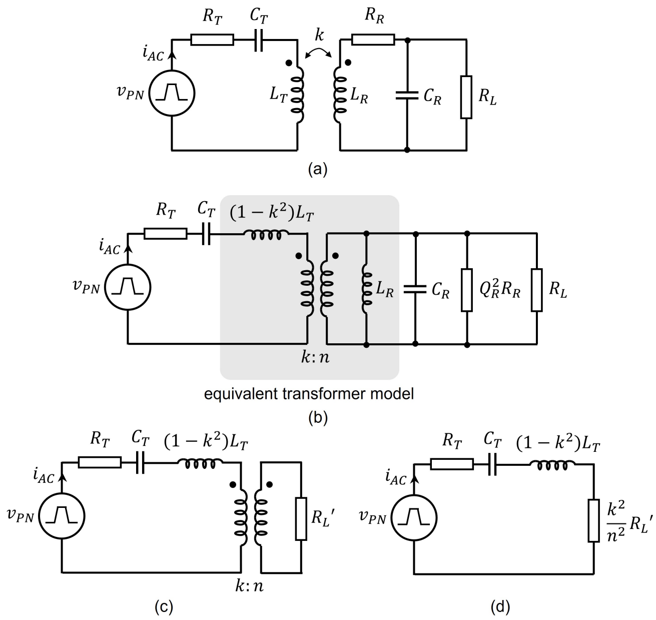

Fig. 6. (a) Series-Parallel resonant inductive link for wireless power transfer, (b) Inductive power link of WPT represented by equivalent transformer model, (c) receiving side resonant components cancelled out and (d) simplified equivalent load model of series-parallel load network.

of WPT load network [5]. Class-PN is a voltage source converter (VSC) topology, therefore a series resonating network has to be selected for transmission side of inductive link. Fig. 6(a) shows series-parallel resonant inductive link for WPT. The transmision side of inductive link (L_{T}) is series compensated by capacitor (C_{T}). For the receiving side of inductive link, parallel resonating network is selected by adding capacitor (C_{R}) in parallel to the receiving coil (L_{R}). k represents coupling co-efficient between the transmission and receiving coils. R_{T} and R_{R} represent series resistance (ESR) in the resonating components on their respective sides. R_{L} in Fig. 6(a) is an RF load to the wireless power transfer system.

In Fig. 6(b) the inductively coupled coils are replaced by an equivalent model with an ideal transformer shown as highlighted portion [14]. This model is used because of its practical ease to transform secondary components into equivalent primary impedance. The turns ratio of the ideal transformer is defined by $k : n$, where n is the turns ratio defined by transmission and receiving side inductance as (7).

$$n = \sqrt{\frac{L_{\mathrm{R}}}{L_{\mathrm{T}}}} \tag{7}$$

Also in Fig. 6(b) series ESR of receiving side resonant components (R_{R}) is transformed to parallel equivalent component $Q_{\mathrm{R}}^2 R_{\mathrm{R}}$, where Q_{R} is unloaded quality factor of receiving side [15]. When the receiving side resonant components L_{R} and C_{R} are tuned for switching frequency ($f_{\mathrm{SW}} = 1/2\pi\sqrt{L_{\mathrm{R}}C_{\mathrm{R}}}$) of the power amplifier, impedance of L_{R} and C_{R} cancel each other out and equivalent load model of Fig. 6(c) is achieved. Here R'_{L} represents parallel combination of original load R_{L} and $Q_{\mathrm{R}}^2 R_{\mathrm{R}}$. Fig. 6(d) shows the final equivalent simplified load model of series-parallel compensated WPT load network. Load R'_{L} is transformed to transmitting side equivalence using turns-ratio transformation. Equivalent load in Fig. 6(d) is similar to series resonant load network used in previous section. Thus, similarly to Sec. IV WPT load can be tuned so that the power amplifier operates in inductive region.

Fig. 7(a) shows the inductive power link designed for WPT. It is a concentric winding type copper tube based design where the receiving side coil is suspended inside the transmission coil. The copper tube outer diameter is 6mm and copper thickness of 1mm. The receiving side coil has 5 turns of diameter 8cm, whereas the transmission side coil diameter is 12cm and consists of 10 turns. For both the transmission and receiving coil uniform turn-turn distance of 6mm is maintained using spacers. The transmission side inductance (L_{T}) value is 8.9μH and receiving side inductance (L_{R}) is 2.3μH. The coupling co-efficient (k) between the two sides is 0.5.

Fig. 7(b) shows the complete WPT load along with the compensation capacitors C_{T} and C_{R} whose value are adjusted to be 125pF and 290pF respectively. This gives the WPT load network a natural frequency (f_0) of 5.5MHz. R_{L} again is a flat chip type RF resistor of value 32Ω. The Class-PN power amplifier is operated at 6.15MHz at 250V DC link voltage. The results are shown in Fig. 8. Transmission side current (i_{AC}) has a peak value of 5.9A. Load resistance (R_{L}) voltage is a sinusoidal waveform due to high quality factor of the WPT load network. The peak of load voltage is 160V

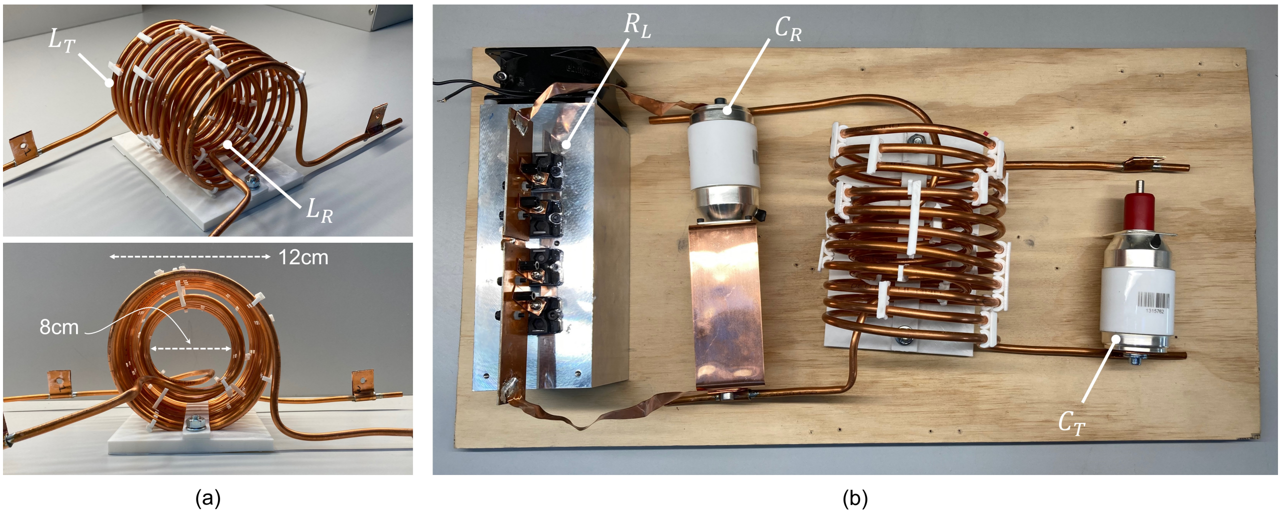

Fig. 7. (a) Inductive power link designed for WPT, receiving coil (L_R) and transmitting coil (L_T) diameter are specified. (b) Series-parallel resonant load for WPT using the inductive power link.

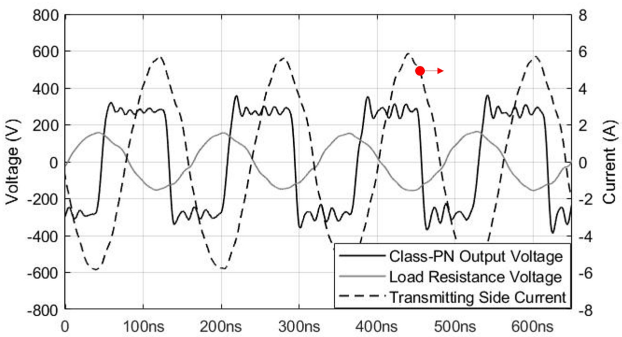

Fig. 8. Class-PN operation with WPT load at 6.15MHz of switching frequency.

which gives 400W of radio frequency power and could not be exceeded due to R_L power rating.

VI. Conclusion

In this paper a new power amplifier topology Class-PN is introduced. This four-switch topology has 4x higher power handling capability than Class-F, Φ, and more than 6x higher than Class-E. As Class-PN power amplifier does not include resonant passive components to achieve soft-switching, same PA can be operated at multiple switching frequencies. Thus the PA is first tested with series resonating load at both 7MHz and 12MHz switching frequency delivering 135W to RF load. Then a WPT load using inductive power link is tested at 6.15MHz of switching frequency. Under WPT load, the PA is delivering 400W to RF load.

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