Transient-free commutation of a resonant-mode array of inductors

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A method and system are proposed for a transient-free commutation of a resonant-mode array of inductors. A single capacitor is used to tune the entire array, and triacs are used to commutate the inductors. To avoid the transients, the tuning capacitor is electrically locked when it stores the whole energy of the excited circuit. This prevents the capacitor from discharge during the fast, 0.1 ms delays, where a triac disconnects the previously excited inductor and another triac connects the next inductor in series with the capacitor. The 0.1 ms delays are defined by the triacs' recovery time. After completing the commutation, the fully charged tuning capacitor is unlocked, and the next excitation cycle begins with no transient. We neglect the short recovery delays and regard the commutation process as transient free. We also show that the recovery delays can further be reduced if the triacs are replaced with faster switching devices. Our experiments with an array of 64 inductors prove the efficiency and simplicity of the commutation method and system. The approach suggested can be useful in instrumentation, power and control magnetics, where a large number of resonant-mode inductors should be quickly commutated.
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I. INTRODUCTION

This work deals with the fast commutation of a large number of induction coils operated at resonance. An application where the above commutation is especially important is magnetic tracking, which recently has caused increased interest in the areas of human-computer interface, virtual reality systems, biomedicine, avionics, etc. The current success of magnetic tracking is related to the possibility of locating single-axial sensors.[1–5] The tracking of single-axial sensors requires the use of numerical algorithms and has become efficient only recently due to the progress in digital signal processing hardware. To provide a fast and unambiguous convergence of the iterative tracking algorithm, a relatively large, redundant number of transmitting coils should be used.[1] The above redundancy may also increase the tracking immunity to magnetic fields retransmitted by nearby conductive objects.

Conventional methods and systems for the commutation of a large number of transmitting coils are rather slow and complex. The main reason for that is the resonant mode of the transmitter operation.

Operating transmitting coils at resonance is generally used to reduce the total coil impedance down to its active part. At resonance, the inductive part of the coil impedance is compensated by a series tuning capacitor. As a result, a relatively low-voltage electronic driver can excite the transmitters with large currents. This provides a large signal-to-noise ratio (SNR) and resolution of the tracking.

The principal disadvantage of the resonant-mode operation is that long transients are involved in the commutation process (see Fig. 1). For a typical magnetic-tracking transmitter with inductance L, resistance R, and quality factor $Q=2\pi f_{ex}L/R$, the commutation transients, $t_{com}=2.2Q/\pi f_{ex}$, are of about 1.2 ms for a $Q=90$. The tracking algorithm suggested in Ref. 1 employs at least eight transmitting coils operated in a sequence. As a result, the operating time for a single transmitter is 2.5 ms at a 50 Hz update rate. The 1.2 ms commutation transients are too long compared to the 2.5 ms operating time. Such time-consuming commutation reduces the average excitation current and the system's SNR. This either slows down the update rate of the tracking or reduces its resolution. A faster, preferably transient-free commutation is necessary to solve this problem.

Another principal disadvantage of the conventional resonant-mode operation[1–5] is that each transmitting coil should be tuned with the individual capacitor. Due to a large excitation current (up to 5 A) and large quality factor of the coil, the tuning capacitor should withstand a high voltage (up to 700 V) applied at a relatively high frequency (up to 50 kHz). Commercially available capacitors that meet these

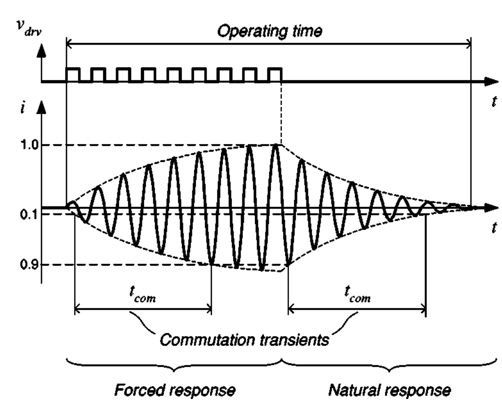

FIG. 1. Conventional commutation of resonant-mode inductors involves long transients.

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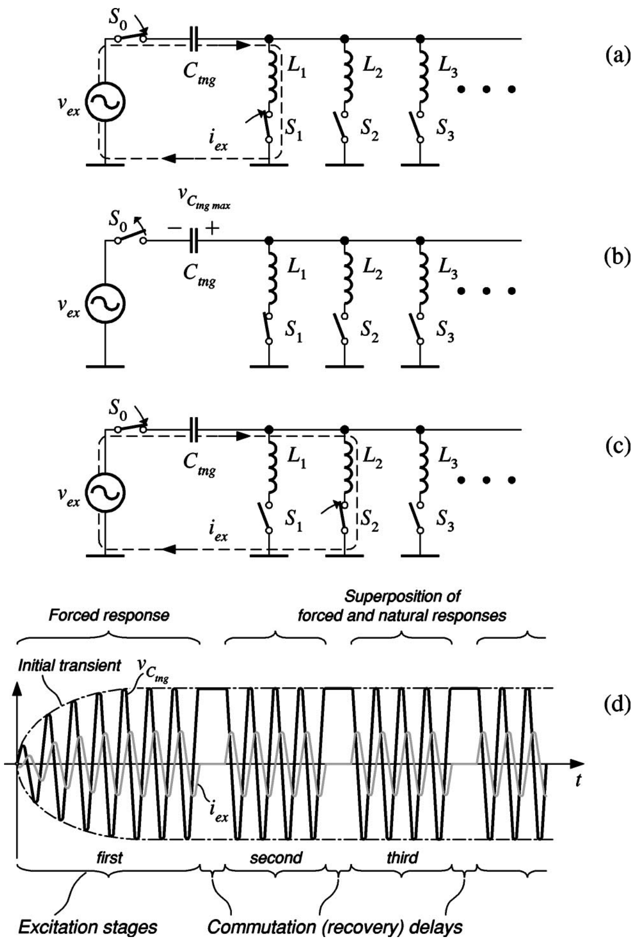

FIG. 2. Commutation method: the commutation of the tuning capacitor and transmitting coils (a) during the first excitation stage, (b) between the excitation stages, and (c) during the second excitation stage, (d) time diagram of the tuning capacitor voltage.

requirements are bulky. Hence, it is impractical to supply transmitting coils in a large array with individual tuning capacitors.

In this work we propose a method and system that allow one to sequentially commutate a resonant-mode array of inductors with no transients and to use a single capacitor to tune the whole array.

Besides of magnetic tracking, the approach suggested can also be used for other applications in the areas of instrumentation and measurements, power and control magnetics, where a transient-free commutation of resonant-mode inductors is essential.

II. METHOD

The method we suggest is based on a very simple idea of storing the maximum voltage built up on the tuning capacitor in the very first excitation stage and then using this voltage as the initial condition in the following excitation stages.

The method is illustrated in Fig. 2, where a number of identical circuits $C_{\text{tng}}L_i$ are sequentially excited at the resonant frequency f_{ex} by the voltage source v_{ex}.

In the first excitation stage [see Fig. 2(a)], the switches S_0 and S_1 connect the first resonant circuit $C_{\text{tng}}L_1$ to the voltage source v_{ex}. We assume that the very first excitation process starts from zero initial conditions and the $C_{\text{tng}}L_1$ circuit natural response is zero. Thus, the circuit's behavior is defined only by its forced response, and this causes a long initial transient [see Fig. 2(d)]. After completing the transient, the voltage on the tuning capacitor C_{tng} reaches a maximum, and the $C_{\text{tng}}L_1$ circuit's time response reaches steady state.

In order to store the maximum voltage of the C_{tng} capacitor reached in the steady state, the switch S_0 disconnects C_{tng} from the voltage source v_{ex} [see Fig. 2(b)] at the moment when the excitation current i_{ex} crosses zero [see Fig. 2(d)].

From this time, the excitation of the coil L_1 is finished, and the commutation of the next resonant circuit, $C_{\text{tng}}L_2$, to the voltage source v_{ex} begins. During the commutation process, the switch S_1 turns off and the switch S_2 turns on. The length of the commutation process (commutation delay) depends on the recovery time of the switches [see Fig. 2(d)].

After the recovery is completed and the v_{ex} phase is the same as it was at the end of the previous excitation stage, the switch S_0 turns on, and the next excitation stage begins with no transient [see Figs. 2(c) and 2(d)]. This is so, because the excitation of the second resonant circuit $C_{\text{tng}}L_2$ starts from the initial state that is equal to the steady state reached in the previous excitation stage. The complete-response transient equals in this case the superposition of the forced-response and natural-response transients (see Fig. 1), which compensate each other.

Although the method suggested may seem very simple and straightforward, its implementation is nontrivial. The difficulty is in synthesizing a simple enough electronic commutation system that will operate at relatively high voltages (up to 700 V), currents (up to 5 A), and frequencies (up to 50 kHz).

III. COMMUTATION SYSTEM

The commutation system [see Fig. 3(a)] we have built and tested comprises 64 transmitting coils L_i, each connected in series with the same tuning capacitor C_{tng}. The triacs X_1 to X_{64} are used to sequentially connect the transmitting coils to ground. The excitation voltage source consists of a half bridge gate driver and the power stage Q_a and Q_b. The microcontroller μC synchronizes the system operation.

The system operation is illustrated in Fig. 3(b). The microcontroller generates the trains of square wave pulses, v_{in}, at the resonant frequency of the $C_{\text{tng}}L_i$ circuits, $f_{\text{ex}} = 51.2$ kHz. During each excitation stage (t_i, t_i'), the voltage source applies the square wave excitation voltage $v_{\text{ex}} = 24$ V zero to peak to the corresponding $C_{\text{tng}}L_i$ circuit. Due to a high quality factor, $Q=90$, of the resonant circuits $C_{\text{tng}}L_i$, the excitation current i_{ex} is of a sinusoidal wave form. When $i_{\text{ex}} = i_{L_i}$ crosses zero, the tuning capacitor is fully charged ($V_{C_{\text{tng}}} = 700$ V) and stores the whole energy of the $C_{\text{tng}}L_i$ circuit.

The excitation stages (t_i, t_i') and (t_{i+1}, t_{i+1}') are separated by relatively short 0.1 ms delay (t_i', t_{i+1}) needed to execute the commutation processes. They start when the excitation current crosses zero. From this moment, the transistor Q_b is

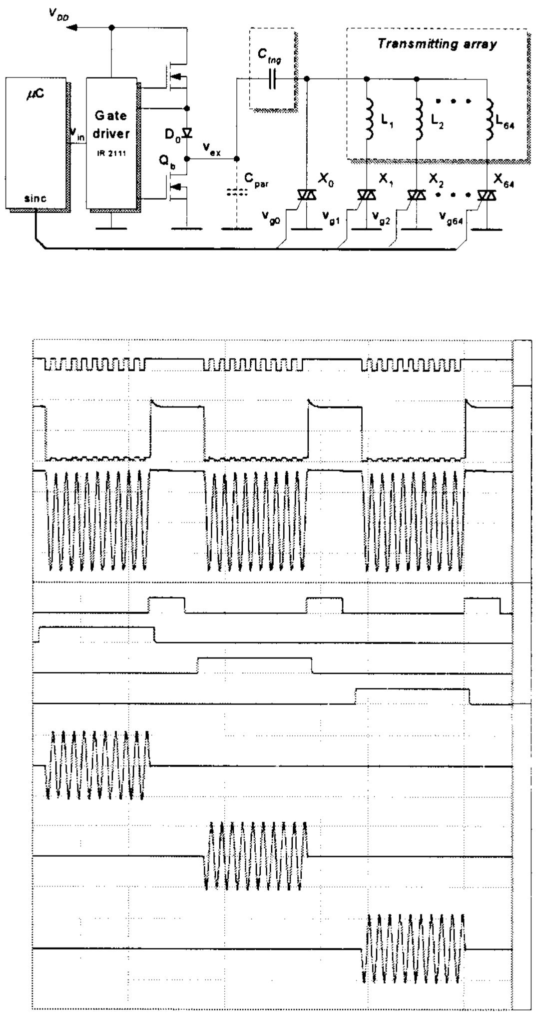

FIG. 3. Implementation of the transient-free commutation method: (a) commutation system and (b) oscillograms.

kept turned off until the end of the commutation. As a result, the capacitor C_{tng} is kept electrically locked by the turned-off transistor Q_b and diode D_0. Since there is no discharge of C_{tng} during the (t_i', t_{i+1}) delay, the excitation current i_{ex} remains zero until the end of the commutation process.

In order to commutate the next transmitting coil L_{i+1}, the triac X_i is turned off and the triac X_{i+1} is turned on. While the latter process is fast, the first one continues for about 60 μs, until X_i fully recovers from the previous conduction stage. The triac X_i recovery time defines the length of the commutation processes (t_i', t_{i+1}).

The next excitation stage (t_{i+1}, t_{i+1}') starts with the turning on of the transistor Q_b by the corresponding pulse train. Q_b unlocks C_{tng}, and the next resonant circuit $C_{\mathrm{tng}}L_{i+1}$ begins to oscillate with no transient.

In the beginning of each commutation process, the triac X_0 is turned on to cancel the parasitic $C_{\mathrm{par}}L_i$ resonance, which may happen when the tuning capacitor C_{tng} is already locked but the triac X_i is still conducting.

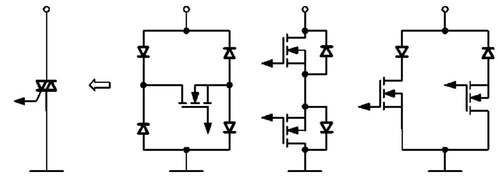

FIG. 4. Replacing the triacs in Fig. 3(a) with faster bidirectional switches can decrease the commutation delays (t_i', t_{i+1}) in Fig. 3(b).

Since the 0.1 ms commutation delays are much shorter compared to commutation transients in a conventional system (see Fig. 1), we neglect them and regard the whole commutation process as a transient free. The 0.1 ms commutation delays can still be reduced further if the triacs are replaced with faster switching devices (see Fig. 4).

IV. CONCLUSIONS

A method and system are proposed for a transient-free commutation of a resonant-mode array of inductors. A single capacitor is used to tune the entire array, and triacs are used to commutate the induction coils. To avoid the transients, the tuning capacitor is electrically locked when it stores the whole energy of the excited circuit. This prevents the capacitor from discharge during the fast, 0.1 ms delays, where a triac disconnects the excited previously inductor, and another triac connects the next inductor in series with the capacitor. The 0.1 ms delays are defined by the triacs' recovery time. After completing a commutation, the fully charged tuning capacitor is unlocked, and the next excitation cycle begins with no transient. We neglect the short recovery delays and regard the commutation process as transient free.

We also show that the recovery delays can further be reduced if the triacs are replaced with faster switching devices.

Our experiments with the array of 64 inductors prove the efficiency and simplicity of the commutation method and device. The approach suggested can be useful in instrumentation, power and control magnetics, where a large number of resonant-mode inductors should be quickly commutated.

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