Filters with Active Tuning for Power Applications

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Abstract— **Passive filters for switched-mode power converters rely on low-pass networks — with corner frequencies well below the ripple fundamental — to attenuate switching harmonics over a range of frequencies. The filters explored in this report provide extra attenuation at *discrete* frequencies, easing the filtering requirement of accompanying low-pass networks. When a converter's switching frequency is tuned to a filter resonance using a novel phase-lock control scheme, a resonant filter can match the ripple-attenuation performance of a low-pass network for less volume, weight, and expense. The applications and limitations of resonant filters and active-tuning control are discussed, and experimental results from the input filter and power stage of a prototype DC-DC converter are presented.**

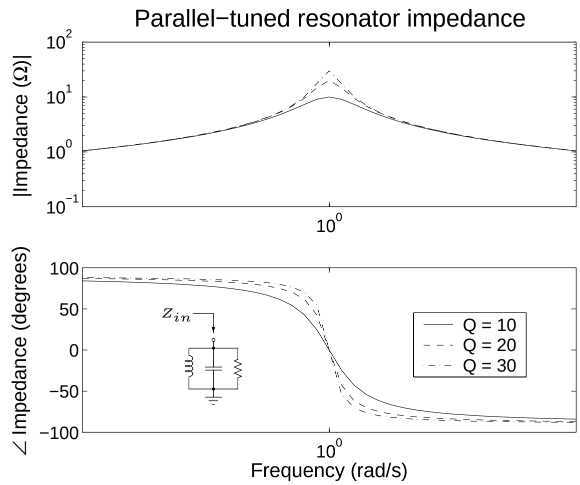

Fig. 1. Frequency response of second-order tuned circuits, normalized to the natural frequency $\omega_n = 1/\sqrt{LC}$. The impedance magnitude at a single frequency can indicate proximity to resonance (with calibration) but not whether resonance lies above or below the stimulus frequency. The impedance phase, however, increases or decreases monotonically, and its difference from 0° is an error signal indicating the distance and direction to resonance.

I. Introduction

LOW-PASS networks have traditionally been employed to attenuate power-converter switching ripple to acceptable levels. Ripple specifications imposed to observe conducted EMI limits or application constraints, however, can result in heavy, bulky filters which are detrimental to the transient performance of a power converter and contribute significantly to its cost. Resonant ripple filters offer attenuation comparable to low-pass networks — for less volume and weight — using the immitance peaking of parallel- and series-tuned circuits (Fig. 1) to introduce transmission nulls at discrete frequencies. Because resonant networks must typically have high Q to attenuate target harmonics sufficiently,[1] they provide only narrow-band attenuation. Operating conditions and manufacturing variations can readily cause narrow-band resonators to miss their design frequencies[2] and fail to attenuate the ripple; for this reason they are rarely employed in switching power converters.

A. Resonant filters with active tuning

The filters described here circumvent this detuning problem by placing a resonator's frequency response or a converter's switching frequency under closed-loop control so that resonant attenuation is always maintained. Filters with active-tuning control can process high power because they modulate a resonance or stimulus frequency to maximize the harmonic selectivity of a passive network: they do not, like active ripple filters ([3], [4], and [5]), directly drive the waveforms they condition. Using the novel phase-lock control scheme described here, actively tuned filters can realize all the advantages of resonant networks, matching the ripple performance of low-pass filters for less volume, weight, and expense.

In this paper we consider the case in which the switching frequency of a power converter is controlled to align with the resonant point of a filter having a series- or parallel-tuned resonance and a reduced low-pass characteristic (e.g., the buck converters of Fig. 2(a) and (b)). Because the resonator effectively

[1]Some high-power applications use damped, low-Q resonators precisely for their broad attenuation characteristic and insensitivity to detuning, at the expense of attenuation performance.[1]

attenuates the ripple-current fundamental, an accompanying low-pass network can be designed with a higher corner frequency and smaller reactances. Inasmuch as suitably low-loss reactive components are available in a small volume, active tuning can reduce the overall size and cost of the input filter compared to a conventional low-pass design.

B. Organization of the paper

Section II of this report introduces a simple phase-lock tuning system which controls the switching frequency of a power converter to operate at the resonant point of a filter. Section III considers the application of the phase-lock approach to the both the power stage and input filter of a buck converter. Experimental results are presented that demonstrate the value of the approach in reducing the sizes of passive components. Section IV considers additional applications and implementations of the phase-lock control system. Finally, Section V presents recommendations for application of the new tuning method.

II. Phase-lock tuning

Resonant excitation is equivalent to maintaining a resistive phase relationship (0°) between resonator voltage and current (note the impedance angles in Fig. 1). Because the phase response of a series- or parallel-tuned circuit monotonically increases or decreases around the 0° tuning point, it can be used as an error signal to control for excitation at the point of maximum immitance. The phase-lock tuning system presented in this paper employs this method precisely, feeding back the phase difference between resonator voltage and current to drive a voltage-controlled oscillator (VCO) toward the resonator's tuned frequency.

A control topology to excite a parallel resonance at its maximum-impedance point (its resistive-impedance point) is depicted in the block diagram of Fig. 3. The phase-lock loop employs a multiplier phase detector and a sinusoidal-output oscillator, and so, with proper limiting of loop bandwidth, produces a quadrature replica of the fundamental voltage across the resonator. When multiplied by the sensed current, only the fundamental components of the the multiplier inputs produce an average output, a product in this case proportional to the phase difference between resonator voltage and current. Multiplier 1 has zero average output (zero error) for a 90° phase shift between its inputs, i.e. zero error for a 0° V-I phase relationship. Because of the resonator's monotonic phase slope, voltage and current measurements with the proper sign always push the VCO towards the resonant frequency. The controlled AC source's

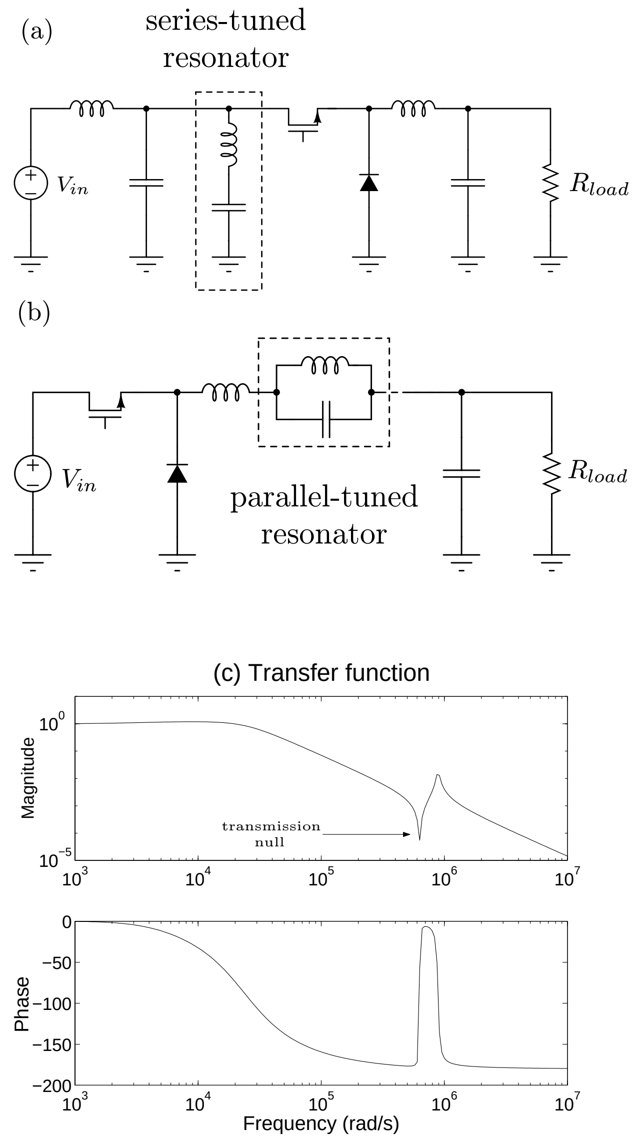

Fig. 2. Example of a series-resonant input filter for a buck converter. (a) The series-tuned leg provides a low-impedance current path (i.e. high attenuation) at a discrete frequency. (b) The parallel-tuned resonator presents a high impedance to switching ripple at a discrete frequency. (c) Transfer function: switch drain current to input current or switch source voltage to output voltage

frequency will therefore be aligned with the tank's resonant point.

In the tank of a practical parallel-resonant filter, as suggested in Fig. 4(a), the inductor is the chief source of loss. Such an "almost parallel" tuned circuit can have a low unloaded Q (< 20) in power applications, and may exhibit the multiple resonant conditions shown in Fig. 4(b) (see caption). The relative frequencies of various tuning points are not in the order shown for all cases, but above a Q of ten, they converge to within a percent of frequency. Tuning

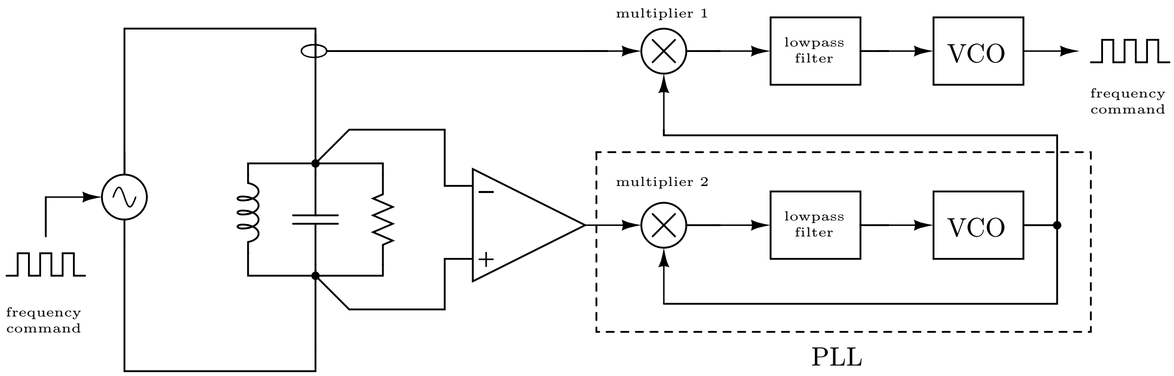

Fig. 3. Block diagram of a phase-lock tuning system.

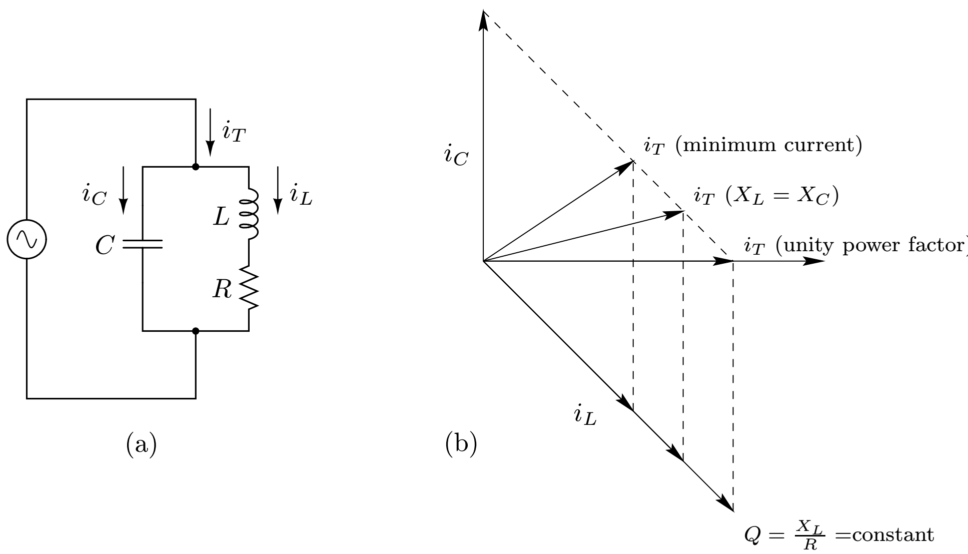

Fig. 4. Tuning points of a parallel-resonant circuit with low unloaded Q. **Note:** for inductor Q values above 10, these resonant points all converge to within 1% of frequency.

Equal reactances $X_L = X_C$ is the tuning condition for series resonators. In the parallel case, the impedance of the inductive leg is composed of X_L and R, an impedance which is greater than — and not 180° out of phase with — X_C. The total current i_T is greater than its minimum value and not in phase with the voltage.

Anti-resonant point (*viz.* maximum impedance resonance). By altering the value of the inductor slightly (and holding its Q constant), a new frequency is found where i_T is minimized and the total parallel reactance is maximized. Again, i_T is out of phase with the voltage.

Unity-power-factor resonant point, found by adjusting the inductance at constant Q so that $X_L + R$ just cancels the capacitive reactance. The value of a parallel-equivalent inductor for this condition is always smaller than the L shown in Fig.4(a), resulting in a resonant frequency different than the other two cases.

for maximum impedance thus results in no appreciable phase difference between the current entering the resonator and the voltage at its terminals: the proposed control scheme can effectively maintain operation where the resonator provides maximum ripple attenuation.

III. Application to a DC-DC converter

A. Filter design

To demonstrate the volume and weight decreases achievable with a resonant filter, the power stage of a 12V-output, 300W buck converter was designed using a tuned-filter approach (Fig. 5). A parallel-tuned resonator placed in series with the load was chosen because its design involved no fundamental trade-off between Q and performance. That is, ripple atten-

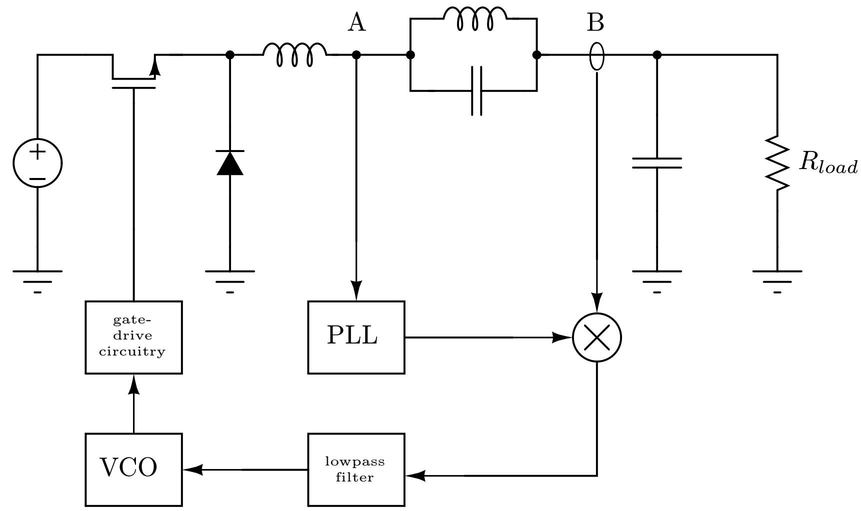

Fig. 5. Block diagram of phase-lock tuning system used to align a buck converter's switching frequency to the maximum-impedance resonance of its output filter. A ground-referenced voltage measurement is made at point A, from which the AC voltage across the tank is determined. The resonator current is measured at point B.

uation increases with Q, the ratio of tuning-point reactance (the characteristic impedance $\sqrt{L/C}$) to tank ESR (equivalent series resistance). The Q of a parallel-tuned network increases with larger inductance, both because a larger resonant inductor will generally have higher Q^2, and because as the resonator characteristic impedance increases, inductor AC flux density and loss decrease. Tuning will be necessary for a high-Q filter, the filter which exhibits the best performance subject to limit on total inductor size.

200μH total inductance — measured at highest saturation — was chosen to limit the size of a resonant filter for the first example converter. This total inductance was split between a low-pass inductor and a resonant inductor (Fig. 6) in the proportion that produced the smallest output current ripple over a duty-ratio range of interest. All inductors were designed to minimize the volume of single-wound, powdered-iron toroids under worst-case operating conditions, i.e. full DC magnetizing force and highest peak-peak AC flux density. Optimization resulted in $L_1 = 235\mu$H and $L_2 = 127\mu$H at 0% saturation. For comparison, a conventional single series inductance L_3 was designed to achieve equivalent ripple performance over the chosen duty-ratio range, resulting in $L_3 = 1.14$mH at 0% saturation. A small polypropylene capacitor C (0.033μF) was chosen to resonate with L_2 near 100kHz, and produced tuning points in the range of 108-131kHz as L_2 saturated under increasing DC bias.

As with any multi-inductor network design, inductor losses depend strongly on AC currents which themselves depend on Q — impedances establish currents, and currents affect impedance. In the resonant-network case, this mutual dependence is steep: high-order transfer functions with lightly damped poles relate the impedance to the current, and core loss (hence ESR) is a strong function of the peak-to-peak AC current (through AC flux density). A simple exponential loss model, $Q = 4.4025 I_{rpp}^{-2.378}$, was constructed from the design of many inductors under bias conditions like those in the filter, and used to simplify the iterative, coupled network/magnetics design.

A more straightforward design is possible whenever the ripple ratios are so low (typically $< 1\%$) that the designer can consult manufacturer's core sizing charts for DC applications. Input and output filters often satisfy this low ripple requirement, so an input filter for the prototype 300W buck converter (Fig. 7) was also built to demonstrate the volume savings achievable with a resonant network under a low-ripple condition. A low-pass inductance L_3' of 72μH was required to meet the ripple performance of the resonant design: a tank inductance $L_1' = 5.4\mu$H and an attenuated low-pass inductor L_3' of 15.4μH.

B. Control design

The control design focused on achieving stable, reliable locking of the converter switching frequency on the filter resonant point. See [6] and [7] for a

[2]For a given core geometry, losses increase roughly as turns and inductance as turns squared, highlighting the general trend that larger inductances are realizable with (relatively) lower loss.

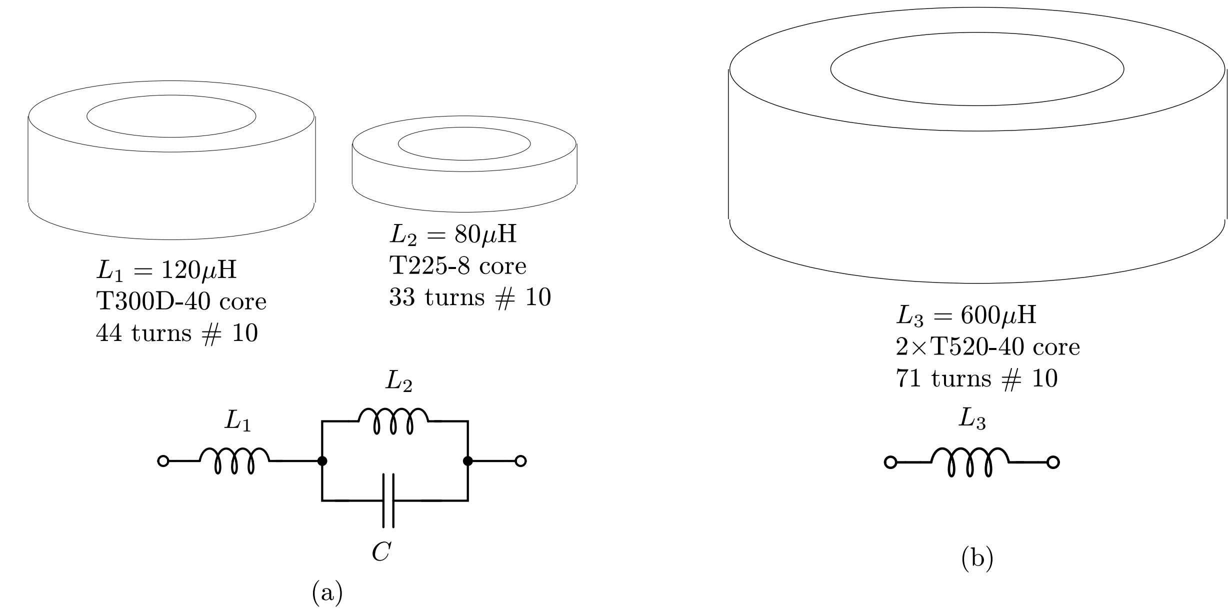

Fig. 6. Comparison of the core sizes for (a) resonant/low-pass and (b) simple low-pass magnetics for the power stage and input filter (primed values) of a 300W buck converter

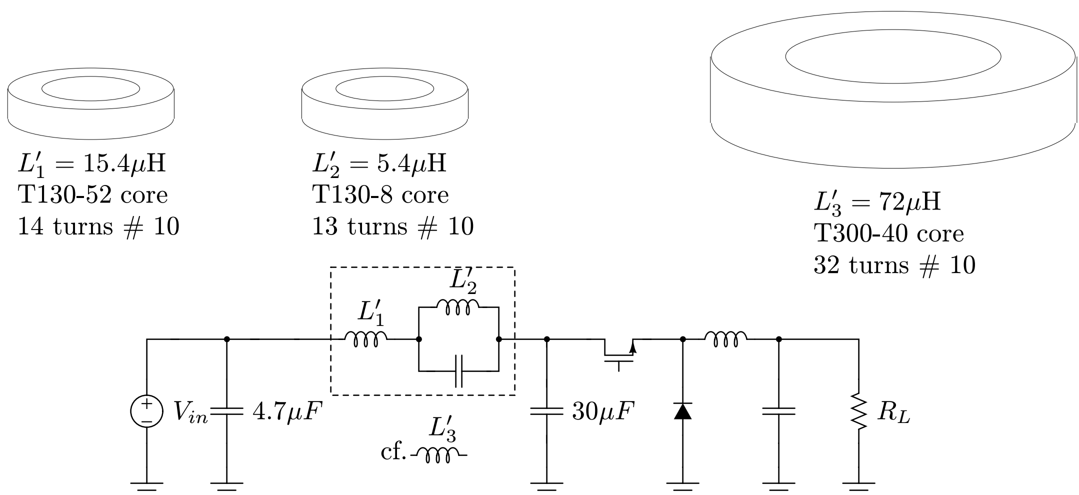

Fig. 7. Resonant input filter design for the prototype 300W buck converter

discussion of the modelling and design of the linear PLL of Figs. 3 and 5. An active proportional + integral (PI) loop filter was chosen to minimize steady-state phase error, and the PLL bandwidth was selected such that its lock-in range covered the expected range of resonant frequencies (see schematic, Fig. 10). The linearized tuning dynamics of the outer loop (Fig. 11) exhibit the same lock-in and holding performance trade-offs as the linear PLL. I.e., lower outer-loop bandwidth decreases phase jitter and improves lock-in reliability at the expense of lower lock range, whereas large bandwidth extends lock range at the expense of holding performance. The switching currents of the converter power stage can be a significant source of noise power, and large loop bandwidths can cause the tuning system to lose lock. We have built functional systems, however, without using the special pull-in techniques often required for noisy signals.

C. Experimental results

As seen from the measured current ripple in Fig. 8, both the resonant power stage and single buck inductor meet a challenging 120mA maximum-ripple-current specification for all duty ratios greater than 0.38. The ripple-current fundamental has the largest

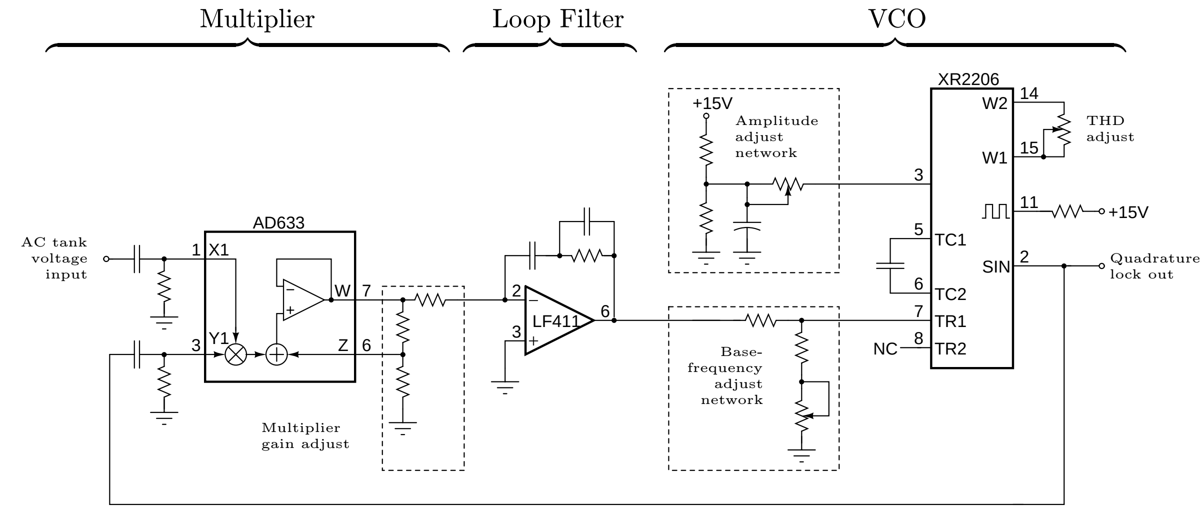

Fig. 10. Schematic of the PLL used in the prototype tuning system.

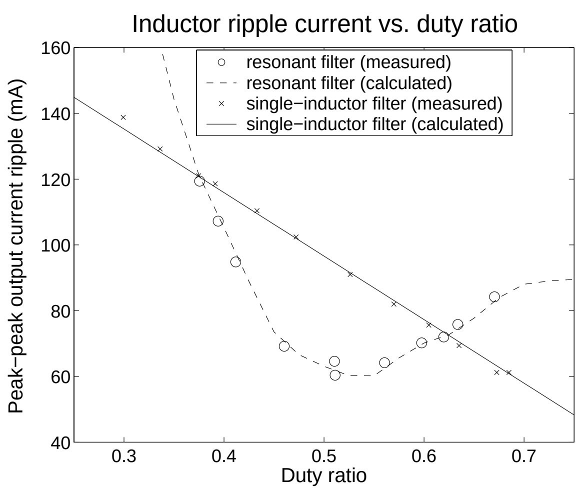

Fig. 8. Comparison of the peak-peak inductor ripple current performance of the single-inductor and resonant power stages.

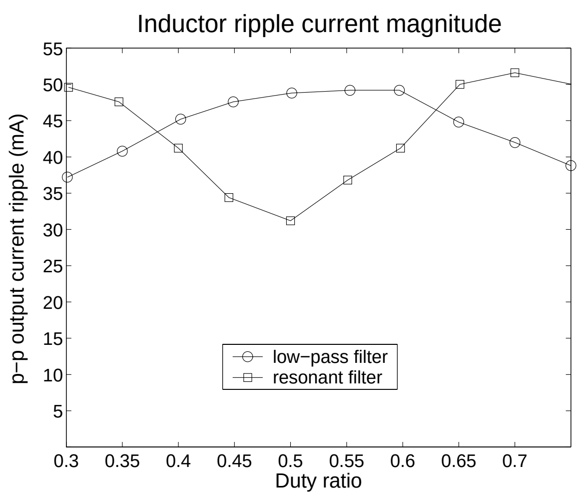

Fig. 9. Comparison of the peak-peak ripple performance of the single-inductor and resonant input filters.

magnitude at $D = 0.5$, around which point the resonant filter obtains the greatest benefit from its parallel-tuned network and outperforms the single inductor at each duty ratio in the range $0.38 < D < 0.62$. The resonant network with active tuning achieves this performance for 3.67 times less total filter volume and 3.3 times less total filter mass than the conventional single inductor.

Similar size improvements were obtained when the resonant-filter technique was applied to the buck converter input filter (Fig. 7). The resonant input filter matched the performace of its low-pass counterpart (Fig. 9) for 2.98 times less core volume and 3.13 times less core mass. If less dramatic core volume and weight improvements are acceptable, either resonant system could match the performance of a single-inductor design over a wider range of duty ratios.

Circulating currents in the parallel-tuned tank are Q times larger than the AC currents at the resonator terminals, so the presented approach is most advantageous when the percent current ripple is required to be small or is already small. Low inductor current ripple is typical for converter input and output filters and for the power stages of converters designed for heavy continuous-conduction mode (i.e. heavy CCM, or small ripple ratio [8]). The designer can therefore apply resonators to a power stage for deep CCM that would otherwise require impractically bulky magnet-

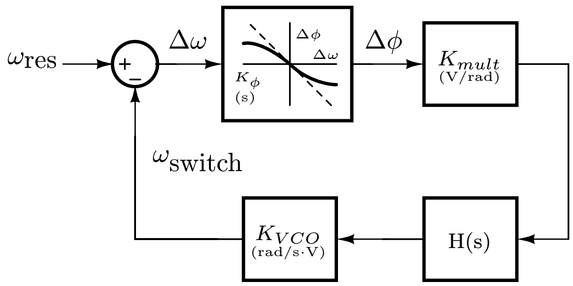

Fig. 11. Linearized tuning dynamics of the phase-sensing control system.

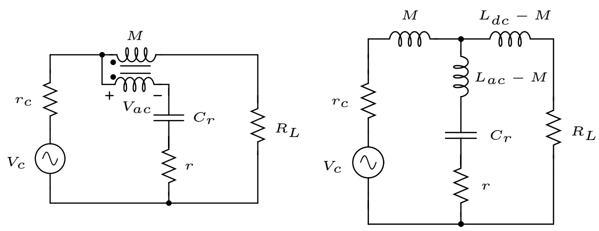

Fig. 12. Magnetically coupled shunt resonator and its equivalent T model, excited by a voltage source V_c representing the switch source node or output of a switching converter.

ics, thus either increasing ripple performance or decreasing the volume of accompanying capacitive elements. The designer can also either reduce the size of input and output filter components (which typically conduct small ripple) or improve filter performance with no increase in volume. Alternatively, the same volume as a conventional design can support — with resonant techniques — a much lower switching frequency for the same EMI performance, thus realizing a substantial improvement in efficiency.

Reduction of filter inductance (cf. L_3 and the combination of L_1 and L_2 in Fig. 6) also improves converter control characteristics. The resonant network provides the attenuation performance of a large inductance (L_3), while presenting an inductance about three times smaller ($L_1 + L_2$) at control frequencies ($\ll f_{sw}$). This smaller reactance permits more rapid transient response (e.g. to load steps) than is conventionally possible at low ripple ratios.

IV. Alternative applications and implementations

A. Shunt resonant filters

The above tuning method is a general technique for controlling the phase relationship of signals, and can be applied to series- and parallel-tuned circuits in the power stages (Fig. 2), input filters (Fig. 7), or output filters of switching converters. Filters containing series-tuned shunt resonators and magnetically coupled shunt resonators (Figs. 2(b) and 12) were also considered for use in conjunction with the phase-lock tuning system. Shunt networks divert ripple current by presenting low AC impedance at the switching frequency and its harmonics. The impedance magnitude of a series-tuned network at its resonant point, not its Q, is therefore the metric of resonator performance. Note that Q can be made arbitrarily high by increasing a resonator's characteristic impedance with inductor-heavy designs: ESR rises more slowly than inductance, so that Q increases, but *ESR still increases*. This performance trend is fundamentally opposed to the need for tuning, as the lowest-ESR design spoils series-tuned Q. The best shunt resonator — the resonator with the lowest possible characteristic impedance — is just the largest possible capacitor, self-resonant at a frequency of particular interest.

B. Resonant Components

Phase-lock tuning can realize the potential benefits of resonant magnetics designs that, like the lumped resonator in the example filter, are otherwise limited by component tolerances. Single-resonant[9] and multi-resonant[10] inductors, for instance, use magnetically coupled tuned circuits to produce high impedances at discrete frequencies. Core-less planar transformers[11] and core-less twisted-coil transformers[12] exhibit resonant maximum-efficiency points characterized by resistive V-I phase relationships at their ports. Variations in driving circuitry, manufactured geometry, DC magnetizing force, AC flux density, and temperature could all alter the tuning point of these resonant structures to such a degree that their resonant properties may be of little benefit in a practical system. With active-tuning control for *excitation at resonance*, the full filtering benefits of these structures can be practically realized.

C. Resonance Tuning

Phase-sensing control can be applied to tune a filter resonant frequency rather than a converter switching frequency. For instance, an electrically controlled reactance implemented with a cross-field reactor (Fig. 13, and see [13], [14], and [15]) can shift a filter transmission null as currents are applied to its control winding. A nested PLL topology like that presented for the frequency tuning case can excite the network containing the cross-field reactor to achieve controlled operation at resonance. An advantage of the resonance-tuning approach is that it can support tuned attenuation of multiple frequencies using multiple resonant networks. Magnetic tuning may also be valuable in coupled-inductor filters and ripple-current steering structures ([16], [17], and

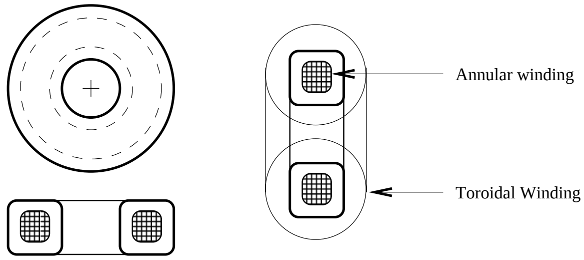

Fig. 13. Structural diagram of a cross-field reactor. The magnetic core is wound with two windings (an annular coil and a toroidal coil) that are not coupled in the usual sense.

[18]) where control of coupling can improve performance.

V. Conclusion

By modulating a switching frequency or filter resonance to maximize a resonant-network immitance, phase-lock tuning makes practical the inclusion of narrow-band resonators in passive ripple filters. Filters with active tuning offset resonant-point variations caused by manufacturing tolerances and fluctuating operating conditions, and so can realize — repeatably and without compromised ripple performance — the size and weight decreases possible with resonant networks and magnetic structures. As demonstrated by the power stage and input filter designs in the prototype converter, a tuned filter can meet the same ripple specification as a conventional design with only one third the mass and volume.

The phase-lock resonant-excitation technique requires an additional control loop, but no additional power-processing devices in its frequency-modulating form. PWM controller ICs could be augmented to accept voltage- and current-ripple waveforms with as few as two pins (for ground-referenced signals). The remaining control elements — multipliers, signal filters, and VCO's — are integrable with no external connections if the loop-filter bandwidths are predetermined. The lighter and less bulky reactive components of actively tuned filters certainly justify this extra control circuitry whenever power quality and converter size and weight are top priorities.

Acknowledgments

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