ISSUE: December 2021

# Modern Control Methods For LLC Converters Simplify Compensator Design

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Resonant converters are found in many power structures with output power levels from a few hundred watts up to several kilowatts. Applications include offline power adapters for game consoles, power supplies for wide-screen flat panel TVs and, more recently, high-wattage charging stations for electric vehicles. Among the possible architectures, the LLC converter has gained popularity owing to the many integrated circuits now available on the market. With its nice sinusoidal waveforms, this converter supports soft-switching and EMI-friendly applications.

This article reviews the techniques available to control LLC converters and provides an overview of recommended controllers available from a range of suppliers. The discussion begins by explaining the principles of operation for an LLC converter, using the most basic form, the LLC half-bridge as an example. In this section, the traditional method of modulating the LLC converter's switching frequency, direct frequency control, is described and its complex requirements for compensation are noted.

With that as background, more up-to-date LLC operating methods including bang-bang charge control, charge-current-mode, current-mode and time-shift control are described. By changing the ac response of the LLC converter, these control techniques simplify the required compensator design, while providing other benefits such as faster transient response. Implementations of these control methods are illustrated using several of the newer LLC controller ICs, some of which also implement PFC control.

## Summary Of LLC Converters: A Third-Order Architecture

As its name implies, an LLC converter is made of three energy-storing elements: two inductors and one capacitor. When connected in series, these elements form a resonating tank characterized by a frequency-dependent gain exhibiting several resonant peaks. A typical configuration for an LLC converter is shown in Fig. 1.

In this example a half-bridge configuration made of two transistors is used to chop the input source into a high-voltage 50% duty ratio square wave feeding the series-resonant tank. A half-bridge configuration will typically let you deliver 500 to 600 W while a four-transistor full-bridge and its derivative can boost power capability beyond the kilowatt.

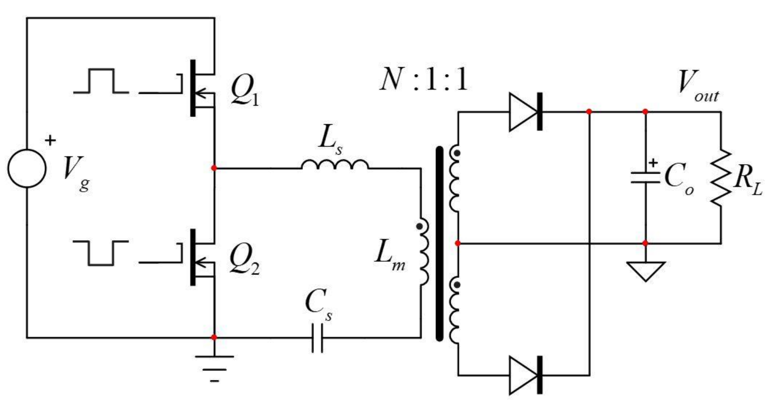



*Fig 1. An LLC converter features three energy-storing components and a transformer.*

Years ago, the upper-side transistor $Q_1$ was typically driven by a pulse transformer considering the need to provide a gate-source bias level referenced to the switching node. High-voltage drivers are now commonly included in modern controllers, but low-voltage versions also exist, especially for secondary-side control. Where higher output current capability is needed, or very high efficiency, the output diodes in this tapped-transformer version can be replaced with synchronous rectifiers.

In Fig. 1, you can see that the transformer magnetizing inductance $L_m$ plays the role of the second inductor. While the circulating magnetizing current can incur too-high core losses, it needs to be sufficiently strong to properly discharge the parasitic capacitance across the MOSFET drain-source terminals during the resonant phase. If adequate dead time is selected, then zero-voltage switching or ZVS of the transistors is achieved.

It is possible[1] to model the LLC converter with an impedance divider whose gain depends on frequency. Using this concept and modulating the switching frequency while keeping an exact 50% duty ratio (ignoring the necessary dead-time) provides a means to adjust the output power flow. Controllers from previous generations used this variable-frequency approach and included a voltage-controlled oscillator (VCO) whose input was driven by the error amplifier for regulation purposes. Examples of popular controllers using this technique include the NCP1395 and NCP1396/97 from onsemi or L6598 and L6699 from STMicroelectronics.

This *direct frequency control* or DFC implies a complicated control-to-output transfer function whose order and expression depends on the operating frequency with respect to the series resonating frequency. Although relatively easy to understand, correctly compensating DFC stages requires a type 3 compensator. Correct compensation can be difficult to achieve and often requires a limit to the control loop 0-dB crossover frequency, leading to rather slow systems whose transient response varies in relationship with the operating point.

## *Bang-Bang Charge Control Technique*

Another possibility to control the LLC converter consists of looking at one of the state variables to infer the power delivered to the load. If the voltage across the resonant capacitor is sampled when it crosses two specific thresholds—when the low-side switch turns off and when the upper switch also turns off—it is possible to show that the net electric quantity absorbed from the source depends on the voltage difference between these two levels. This is the principle behind the so-called *bang-bang charge control* technique[2] implemented by NXP in its popular family of combination PFC+LLC controllers.

The most recent product release using this LLC control technique is the TEA2017. The TEA2017 supports multi-mode PFC capability including discontinuous conduction mode (DCM), borderline control mode (BCM) and continuous conduction mode (CCM) PFC control alongside the integrated LLC controller. By symmetrically setting high- and low-voltage thresholds while observing a scaled-down image of the capacitor voltage, it is possible to regulate the power flow via the control loop.

Using this approach, the switching frequency is *indirectly* controlled and consequently, the control-to-output ac response is a simpler-to-control first-order system. Fig. 2 shows the simplified electrical diagram extracted from the TEA2017 data sheet.

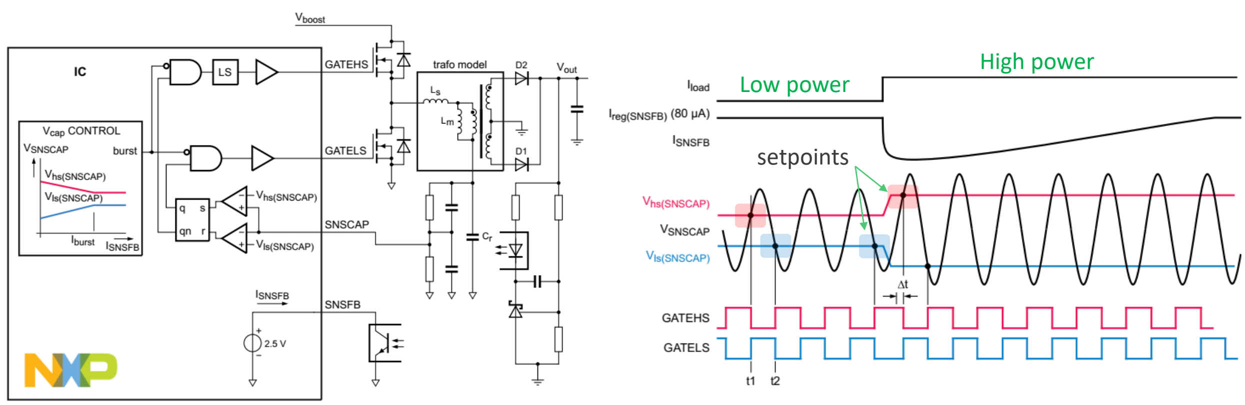



*Fig. 2. The TEA2017 LLC and PFC controller adjusts the two voltage thresholds via an optocoupler absorbing current from the SNSFB pin.*

The feedback pin offers a fixed voltage bias and monitors the current absorbed by the optocoupler. A proprietary scheme keeps this current to 80 µA, on average, and ensures the lowest standby power. Feedback control for the TEA2017 requires a simpler approach using a type 2 compensator (rather than the type 3 required for conventional DFC LLC) and supports more flexibility to arrange a higher 0-dB crossover frequency for the control loop thus improving transient response of the stage.

A further benefit of the TEA2017 lies in its high average efficiency performance compared to what other controllers provide. As output load drops, a high value of efficiency is maintained. In recent measurements taken at Future Electronics center of excellence (CoE), a four-point average efficiency of 94% was achieved at a 230-V rms input using NXP's evaluation board and adjusting its design to meet a 250-W load requirement at a 42-V output.

## *Charge Control Approach*

If a controller is designed to integrate the instantaneous current $i_C(t)$ flowing in the resonating capacitor, the capacitive charge $Q$ averaged across a switching cycle becomes a useful measure for regulation purposes. When the peak of the integrated waveform is reset cycle-by-cycle and compared to a dc voltage set by the error amplifier, an external loop can regulate the converter based on the output demand. This is the *charge-current-mode* control regulation principle used in onsemi's NCP4390 and described in reference 3.

As shown in Fig. 3, a current-sense transformer monitors the current flowing in the resonant tank and enters the controller via an integrating time constant set by an external *RC* network. The capacitor is discharged cycle-by-cycle and ensures sampling at the current switching frequency. Supplemented by a compensation ramp, the resulting waveform is then compared to the dc voltage delivered by the error amplifier to generate a reset to the main pulse-width modulator (PWM) latch.

This circuitry guarantees the absence of subharmonic oscillations with a perfect 50% duty ratio. The ac response of the LLC power stage operated in this mode is that of a damped second-order system which lets the designer choose a simple type 2 compensator. It also supports more flexibility to arrange a higher crossover frequency for the control loop thus improving transient response of the LLC stage.

The NCP4390 is a low-voltage die and can be used in the secondary-side of the converter. In this configuration, a pulse transformer or another isolated means to drive the primary-side switches is required. A current-sense transformer provides an isolated measurement of the resonant current. When located on the secondary side of the LLC converter, the output voltage is sampled directly and driving synchronous MOSFETs is made simpler. As such, this controller is a recommended choice for high-power applications, typically exceeding 1 kW.

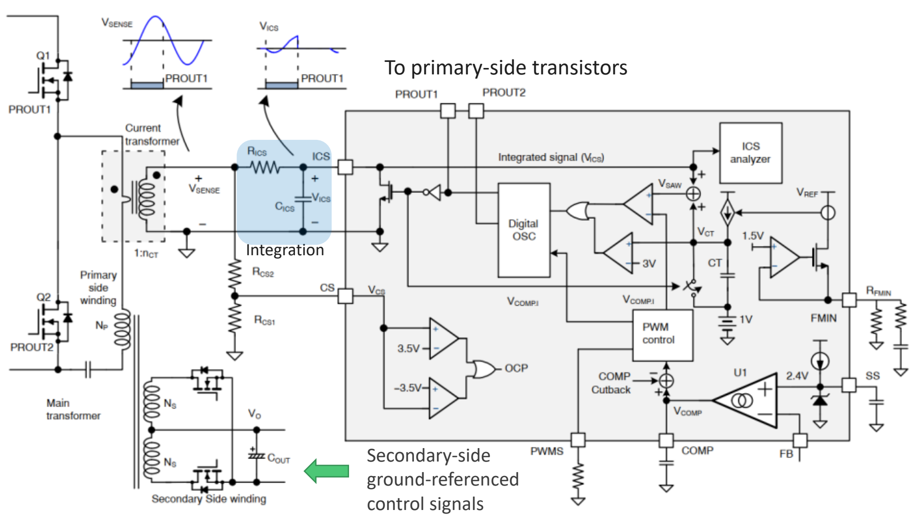



*Fig. 3. From onsemi, the NCP4390 controller for LLC resonant converters operates by setting the peak value of the integrated capacitor current supplemented by an artificial ramp.*

## *Current-Mode Control*

The strategy adopted by another controller, the NCP13992 from onsemi, differs from the previous implementations. The part sets a threshold for the resonant capacitor voltage observed through a differentiating divider. This threshold is then classically set by the error amplifier and adjusts the peak current cycle-by-cycle. The loop adjusts the power flow and indirectly fixes the switching frequency. A compensation ramp is provided to damp any subharmonic instabilities. The ac response is first order and easy to compensate allowing the designer to select a high 0-dB crossover frequency in the control loop, compared with DFC LLC.

The differentiation offered by the NCP13992 lies in its switching pattern elaboration: the time during which the upper-side MOSFET remains on is internally recorded with a precise resolution step. At the end of the on-time, the low-side transistor turns on for the exact same duration with an automatic deadtime selection for ZVS operation. That way, a perfect 50% duty ratio is ensured in all operating conditions.

The tight dead-time control can be used to improve overall efficiency. It also makes the NCP13992 suitable for driving GaN transistors and arranging faster switching frequency operation for the LLC stage. A faster switching frequency supports a smaller transformer design and increases the power density of the LLC stage.

The principle of operation is shown in Fig. 4 while a typical application schematic featuring synchronous rectification appears on the right side. Although located on the primary side of an LLC stage, the NCP13992 does not include a PFC controller. If PFC control is required, this must be accommodated by a dedicated integrated circuit.

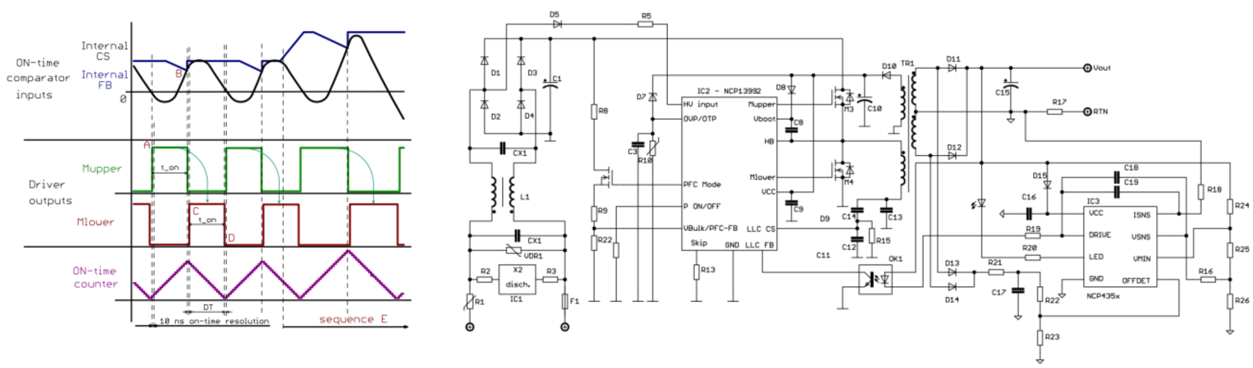
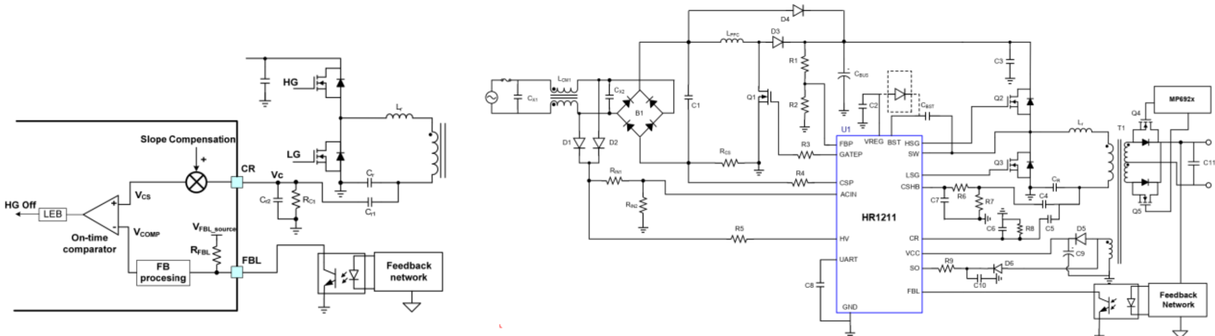



*Fig. 4. The NCP13992, a resonant controller with integrated high voltage drivers, uses a current-mode control core to regulate the output power.*

If the customer seeks to employ current-mode control and a combined PFC+LLC converter functionality, current-mode control is also implemented in the recently-released HR1211 from Monolithic Power Systems. The HR1211 measures the voltage developed across the resonant capacitor and adjusts the on-time duration of the upper-side switch in relationship to the output power (Fig. 5). An internal counter ensures the perfect mirroring of the on-time to determine the conduction duration of the low-side transistor. However, slope compensation is necessary for ensuring operation free from subharmonic oscillations.




Current-mode control section

Typical high-power application

*Fig. 5. The HR1211 is a combo controller whose LLC section operates in current-mode control.*

Fig. 5 illustrates the current-mode section of the HR1211 on the left side of the figure while the right side depicts the combo chip in a generic power adapter. The part implements a digital core featuring a multiple-time programmable (MTP) memory and a nonvolatile memory (NVM). The HR1211 provides a standard universal asynchronous receiver transmitter (UART) which allows the communication with a dedicated graphic user interface (GUI). Using this facility, the power supply designer can choose the parameters he needs for the control of the PFC and LLC stages. The PFC controller in the HR1211 employs a patented, digital average-current control scheme to achieve hybrid CCM/DCM operation.

## *Time-Shift Control*

ST Microelectronics employs a different solution in which the control loop no longer sets a frequency, but a delay. They designate this control strategy as a *time-shift control* (TSC) LLC. When the on-time is initiated, an oscillator internal to the controller starts charging its capacitor while the resonant current ramps up from a negative to a positive value. When the timing capacitor reaches its upper threshold at which point it should normally turn the upper switch off and initiate a downfall, the current sense comparator prevents this from happening and keeps the capacitor charge at its upper level, marking a pause in the cycle.

When the current comparator eventually toggles, implying a positive-going current, the capacitor is freed and can discharge, initiating the off-time during which the low-side transistor is activated. During the off-time the scenario is reversed: when the capacitor reaches its lower threshold, it stays there as long as the current is positive. When the current crosses zero again, then a new cycle takes place. Fig. 6 below shows how this operation is performed by adding some logic gates around a classical oscillator structure.

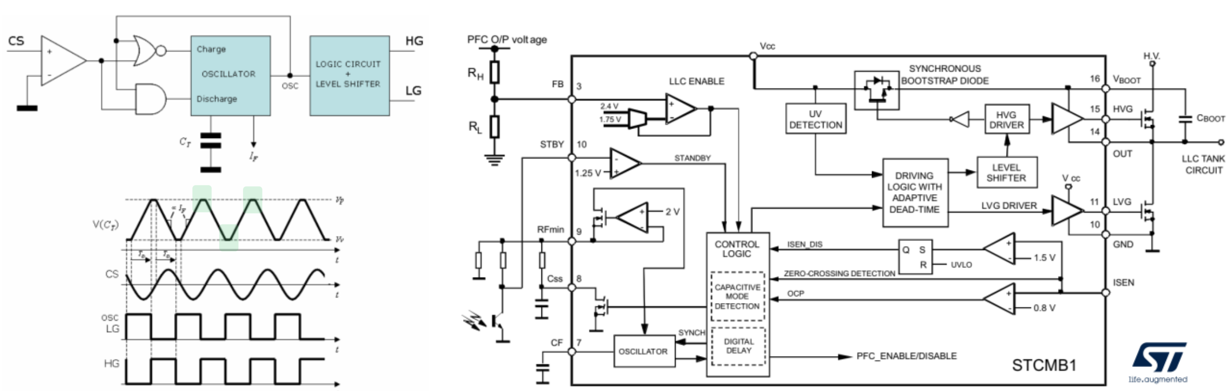



*Fig. 6. As implented in the STCMB1 transition-mode PFC and LLC resonant combo controller, ST's proprietary modulator inserts a delay in the switching pattern and adjusts it for loop control.*

The right-side of the figure shows the LLC section of this combo chip, the STCMB1, which implements a continuous conduction mode (CCM) PFC for the front-end section. As with the previous parts, TSC eases the control strategy by making the LLC ac response that of an overdamped second-order system allowing for a type 2 compensation strategy.

## *Conclusion*

This short overview presents the control methods currently implemented in some commercially-available controllers. While direct frequency control was the method of choice twenty years ago, new techniques now dominate the market and make the compensation of an LLC converter a simpler exercise than before. Future Electronics power specialists will guide you in selecting the right topology for your end product application while suggesting part numbers suiting your needs.

**References**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**About The Author**


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*For further reading on LLC converter design, see the How2Power Design Guide, and do a keyword search on "resonant."*