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Parallel tuned contactless power pickup using saturable core reactor

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Abstract **- This paper proposes a novel contactless secondary power pickup designed for inductively coupled contactless power transfer systems. It is based upon parallel LC tuning with the equivalent capacitance varied by a saturable core reactor (SCR). The proposed technique allows the power pickup to achieve full-range operation for power flow regulation and maintain constant output voltage at a high quality factor Q. The method eliminates the tedious fine-tuning process associated with traditional fixed power pickup tuning methods and eases the component selection. Moreover, it can overcome the online circuit parameter variations and automatically achieve the maximum power transfer capacity when required. In order to meet dynamic load demands, the SCR is controlled to be a variable inductor. A simple algorithm is developed to change the tuning condition of the power pickup. The effectiveness of the proposed power pickup and its applicability to general wireless power transfer applications has been demonstrated by both simulation and experimental results.**

Index Terms – Contactless Power Transfer, Inductively coupled power transfer (ICPT) systems, **saturable core reactor (SCR), linear control.**

I. INTRODUCTION

INDUCTIVELY coupled power transfer (ICPT) systems are designed to deliver power efficiently from a stationary primary source to one or more movable secondary loads over relatively large air gaps via magnetic coupling. It is based on the fundamental principles of electromagnetism discovered by Ampere and Faraday that make use of alternating magnetic fields around current carrying conductors to transfer power from a primary winding to a secondary winding.

Modern power electronics have enabled many new applications such as contactless power supplies for professional tools, contact-less battery charging across large air-gaps for electric vehicles, compact electronic devices, mobile phones, and biomedical implants [1, 2, 3 and 4]. Other examples include material handling systems and public transport systems where the secondary systems are electrically isolated and move along a long track. The advantages of such systems are safety, reliability, low maintenance and long product life.

The mutual coupling of ICPT systems is generally weak. To deliver the required power and ensure equipment size remains manageable, it is necessary to operate at a high frequency. In addition, resonant circuits are normally employed in the primary and/or secondary networks to boost the power transfer capability, while minimizing the required VA rating of the power supply.

This paper is about dynamic tuning control of a parallel tuned power using a saturable core reactor (SCR).

II. FUNDAMENTALS OF ICPT SYSTEM

A. *Block Diagram of an ICPT system*

The general structure of a loosely coupled ICPT system, as shown in Fig 1, comprises of two galvanically isolated but magnetically coupled systems. In such systems, electrical power is transferred from a primary winding in the form of a coil or track, to one or more isolated pick-up coils that may move relative to the primary. The primary winding (stationary track or coil) is normally compensated in order to minimize the VA rating of the supply. Compensation of the secondary winding (movable pickup) enhances the power transfer capability of the system. In more complex systems many individual pickups can exist, supplied by a single track.

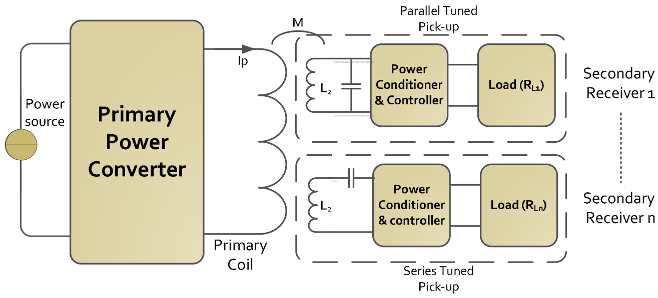


Fig. 1 Block Diagram of ICPT System

B. *Power flow control in existing ICPT system*

Two most common compensation topologies used in pickups are parallel and series tuned systems as shown in Fig 1. Parallel tuning gives a constant current source property while series tuning gives a constant voltage source property [4]. For a series tuned pickup, the voltage source property is ideal for driving most common types of loads. However, even in series tuning it is difficult to exactly match the induced voltage of the pickup to the desired output voltage as the tolerance in the inductor windings can easily create a 10% deviation in the output voltage [5], and in the case of parallel tuning the load variation further changes the output voltage. The output voltage variation may not be acceptable for many commercial or industrial loads. Therefore, a power controller is usually used to regulate the output voltage to a desired reference. Power flow control may be implemented at the primary stationary side, but it eliminates the possibilities of ICPT systems to have multiple pickups operation, unless all the pickups are absolutely identical in operation which is unlikely to happen in practice.

There are many secondary controllers previously developed for ICPT systems which can regulate the output voltage. The majority of these are parallel tuned pickups such as the decoupling/shorting controller [1], switched mode controller [6], etc.

An alternative control method which has been investigated to improve the power flow control of ICPT systems is the dynamic tuning/detuning control technique proposed in [2, 3, 7 and 8]. Instead of fine-tuning the power pickups to obtain the maximum power and then controlling it to meet the load requirements, this control strategy regulates the pickup such that it only takes sufficient power required by the load. Theoretically, if the maximum power is needed, the circuit will be capable of going to the tuned-point where the maximum power can be obtained, and lower output power is achieved by detuning the pickup circuit. The variable tuning conditions of the pickup is attained by deliberately putting a capacitor/inductor in parallel with a fixed tuning capacitor. The variable capacitor or inductor can be achieved either mechanically by altering the geometry or changing material properties, or electronically using semiconductor devices to control current flow through the capacitor/inductor. The former requires the capacitance/inductance to be changed off-line manually, which is not feasible in most of the application scenarios. A semiconductor transistor can be used to control the current flow through the tuning capacitor/inductor so as to vary the tuning component, either by switching the capacitor/inductor in/out of the resonant tank, or by operating in the linear region to function as a variable resistor. But they suffer from low power efficiency, particularly under light-load or no-load conditions, and are incapable of covering the full control range of the tuning curve.

C. Proposed ICPT power pick-up system

A novel technique of achieving variable tuning covering full control range is proposed. The structure of the proposed ICPT power pick-up system is shown in Fig 2. It consists of two related parts - the pickup and the control circuitry. LCL tuning configuration is used to replace the conventional LC tuning circuit, and a saturable core reactor is to function as a variable inductor with the output voltage as a feedback control signal. A feedback controller that can adapt to the bell-shaped curve and track the closest reference point along the power curve for achieving full-range tuning control was developed.

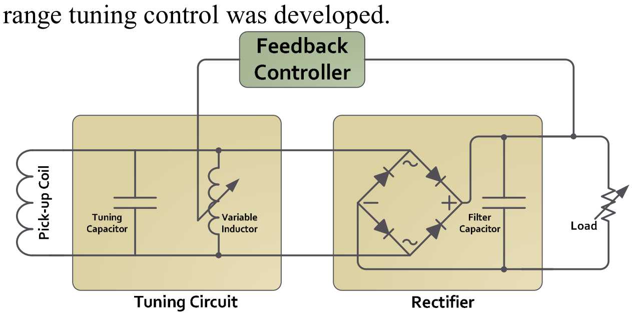


Fig. 2: Proposed ICPT Pick-up unit

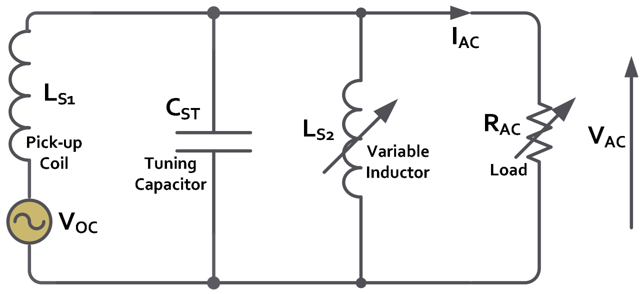


Fig. 3: Proposed ICPT Pick-up unit

III. LCL POWER PICKUP

A simplified model, as shown in Fig 3, can be used to analyze the system without considering the ac-dc rectification. As can be seen from the Fig 3, the general structure of an LCL tuning circuit consists of a secondary pickup coil inductance L_{S1}, a tuning capacitor C_{ST}, and a controllable tuning inductor L_{S2} in parallel with the load. The resistance R_{AC} is the ac equivalent resistance of the dc load R_L. Transfer function of the parallel LCL tuning circuit output voltage and current are given by (1) and (2):

$$V_{AC} = \frac{L_{S2} \cdot R_{AC} \cdot V_{OC}}{s^2 L_{S1} L_{S2} R_{AC} C_{ST} + s L_{S1} L_{S2} + (L_{S1} + L_{S2}) R_{AC}} \tag{1}$$

$$I_{AC} = \frac{s L_{S1} \cdot L_{S2} \cdot I_{SC}}{s^2 L_{S1} L_{S2} R_{AC} C_{ST} + s L_{S1} L_{S2} + (L_{S1} + L_{S2}) R_{AC}} \tag{2}$$

For a fully tuned power pick-up circuit with the parallel LCL configuration, the value of C_{ST} can be regarded as C_{S1} and C_{S2} in parallel, which are used to resonate with L_{S1} and L_{S2}, respectively (see Fig 4). Under fully tuned conditions, i.e., when $\omega^2 = 1/L_{S1}C_{S1} = 1/L_{S2}C_{S2}$, the output voltage can be obtained as:

$$V_{AC} = -jR_{AC}\sqrt{\frac{C_{S1}}{L_{S1}}}V_{OC} = -j\frac{R_{AC}}{\omega L_{S1}}V_{OC} = -jQ_p V_{OC} \tag{3}$$

$$I_{AC} = I_{SC} \tag{4}$$

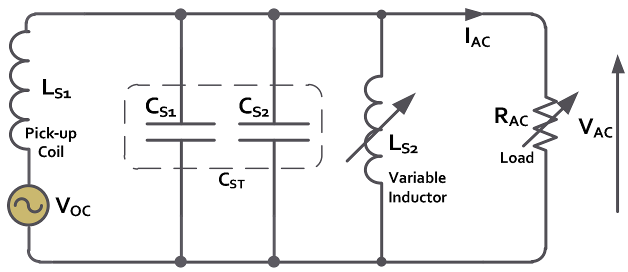


Fig. 4: Abstract splitting of tuning capacitance

The tuning circuit outputs a constant current source, making the output current load independent and is equal to the short circuit current under the full resonant condition. But the output voltage is load dependent. Using (4) the maximum power transfer capacity of the pick-up is determined by:

$$P_{AC,rms} = \frac{V_{AC}^2}{2R_{AC}} = \frac{Q_p^2 V_{OC}^2}{2R_{AC}} \tag{5}$$

It is not difficult to see that the maximum power of the pick-up is controlled by the tuning control inductance L_{S2} which in turn alters the quality factor of the first LC pair, with a reasonable assumption that the rest of the variables are fixed. As such, L_{S2} is justified to be selected as the main control variable in the new system.

The parallel LCL configuration basically behaves as an LC tuning circuit with variable capacitance. It can be shown that to maintain the output voltage constant without shorting the pickup coil in the steady state, the equivalent capacitance should be detuned according to:

$$C_{eq} = C_0\left(1 \pm \frac{1}{Q_p}\sqrt{\left(\frac{Q_p}{k_v}\right)^2 - 1}\right) \qquad (6)$$

where C_0 is the original capacitance for full tuning, Q_p is the quality factor which reflects the load change, and k_v is the actual required boost factor from the open-circuit voltage to the output voltage , i.e., $k_v = V_{AC}/V_{OC}$.

From the fixed amount of capacitance available in the tuning capacitance C_{ST}, a certain amount C_{S2} can be thought to be in resonance with SCR, the rest, i.e. $C_{S1} = C_{ST} - C_{S2}$ will be available for the LC tuning circuit. But for keeping the output voltage constant and delivering the required power to the load C_{S1} must be varied according to (6). So by adjusting SCR appropriately by the feedback controller, the second tuning circuit will change the capacitance from C_{ST} according to the need, thereby varying C_{S1} effectively.

The variation of C_{S1} is centred on C_{S1_0}, which is the resonance value with L_{S1}, i.e. $C_{S1} \in (C_{S1_0} - C_{V_m}, C_{S1_0} + C_{V_m})$. The maximum deviation C_{V_m} is reached when the system is very lightly loaded or open circuit; it is evaluated by letting Q_p tend to infinity (which reflects load resistance going to infinity) in (6), i.e.

$$C_{V_m} = \lim_{Q_p\to\infty} \frac{C_{S1_0}}{Q_p}\sqrt{\left(\frac{Q_p}{k_v}\right)^2 - 1} = \frac{C_{S1_0}}{k_v} \qquad (7)$$

Correspondingly C_{S2} must also vary symmetrically about resonance value $C_{S2_0} = C_{ST} - C_{S1_0}$, i.e. $C_{S2} \in (C_{S2} - C_{V_m}, C_{S2_0} + C_{V_m})$. This value decides the quiescent point of the SCR, i.e. $L_{S2_0} = 1/\omega^2 C_{S2_0}$. But the SCR varies asymmetrically about q-point, due to the inverse relationship between C_{S2} and L_{S2} at resonance, i.e.:

$$L_{S2} = \frac{1}{\omega^2 C_{S2}} = \frac{1}{\omega^2 (C_{ST} - C_{S1})} \qquad (8)$$

The operating range of the SCR that needs to be designed can be evaluated using (8) under extreme values, i.e.:

$$L_{S2\_min} = \frac{1}{\omega^2 (C_{S2_0} + C_{V_m})} = \frac{1}{\omega^2 (C_{ST} - C_{S1_0} + C_{V_m})} \qquad (9)$$

$$L_{S2\_max} = \frac{1}{\omega^2 (C_{S2_0} - C_{V_m})} = \frac{1}{\omega^2 (C_{ST} - C_{S1_0} - C_{V_m})} \qquad (10)$$

IV. SCR Design

A saturable core reactor is a magnetic-core reactor whose reactance is controlled by changing the permeability of the core [9]. It typically consists of two separate winding – control winding and AC inductor - on the same magnetic core.

The permeability of the core is changed by varying a unidirectional DC flux (flux in one direction) through the core. Fig 5 shows the magnetization and permeability curves for typical ferromagnetic materials. The ideal operating region for a SCR is the place where a small change in the control current will cause a large variation in AC inductance. In Fig 5, A-B centred by point Q shows an ideal region that the permeability reduces linearly with the control current.

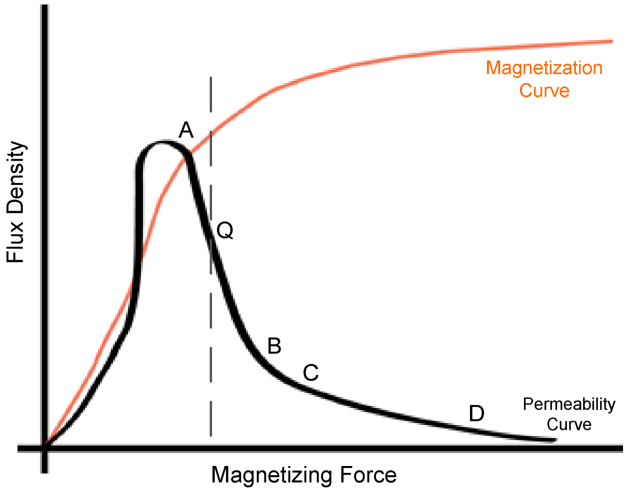


Fig. 5: Magnetization and permeability curves

Working [10]: If a DC voltage is applied to the control winding of a saturable-core reactor, and an AC voltage is applied to the load windings, the AC flux will aid the DC flux on one half cycle and oppose the DC flux on the other half cycle. This is shown in Fig 6. The load flux is indicated by the dashed-line arrows, and the control flux is indicated by the solid-line arrows. View (a) shows the load and control flux adding during one half cycle of the AC, and view (b) of the Fig 4 shows the load and control flux are opposing during the other half cycle of the AC.

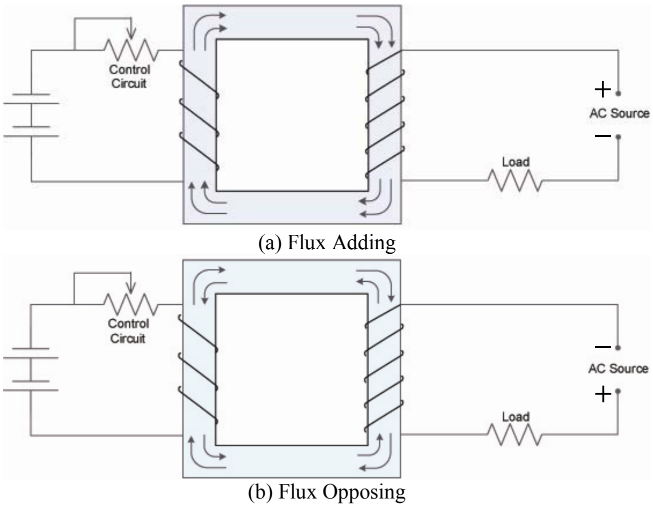
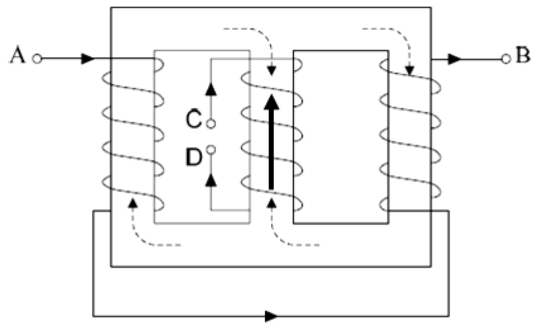
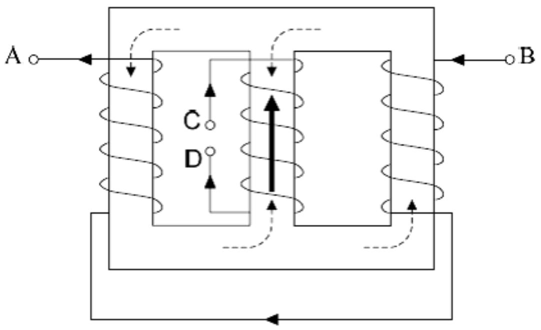


Fig. 6: Flux paths in a saturable-core reactor

This situation causes the operating point of the saturable-core reactor to shift with the applied AC, and the AC voltage may be induced in the DC control circuit. However, the situation would be better if the load flux has no influence on the control flux, i.e., no AC voltage is induced in the DC control circuit.



(A) Current direction: A to B



(B) Current direction: B to A
Fig. 7: Improved SCR design

Fig 7 shows an improved magnetic circuit. Two three legged E-cores are placed leg to leg to form the saturable core reactor. The AC winding is wound on the two outer legs, and DC control winding on the inner leg. Because of this particular arrangement of the power windings, the control winding, and its core is decoupled from the ac power, and thus the AC circuit generates no effect upon the control circuit flux. The AC power windings are configured such that they cancel out AC voltages that would otherwise be induced into the control winding.

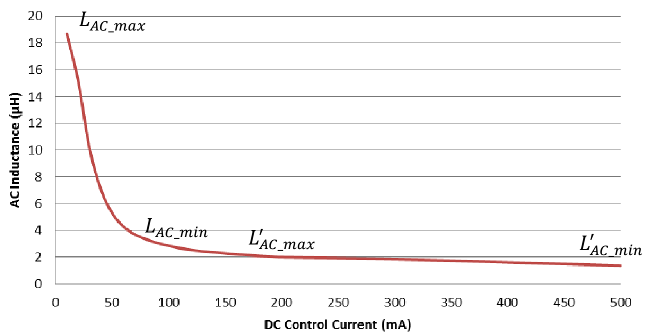


Fig. 8: Relationship between dc control current and effective AC inductance of SCR

One of the design considerations would be the selection of a quasi-linear region from the two sections shown in Fig 6, which are the region between L_{AC_max} to $L_{AC\ min}$ (corresponding to point A to B in Fig 5), and $L'_{AC\ max}$ to $L'_{AC\ min}$ (corresponding to point C to D in Fig 5). However, the region between L'_{AC_max} and L'_{AC_max} requires more current and can only achieve very limited variable inductance. Therefore the preferred operating range of the SCR is selected to lie between L_{AC_max} and L_{AC_min}.

The inductance of the AC winding is determined using:

$$L_{AC} = \frac{\mu_d N_{AC}^2 S}{l} \tag{11}$$

where N_{AC} is the total number of turns in the AC windings, S is the average cross-sectional area of the core, and l is the effective length of the magnetic flux path. Since it is linearly proportional to the permeability of the core, so by restricting the operation in the quasi-linear region, a linear control over AC inductance can be achieved. Thereby controlling the DC bias current through the SCR control windings by appropriate feedback control mechanism the AC inductance can be effectively varied linearly.

IV. Controller

Apart from the physical components design, an algorithm has to be developed to regulate the output voltage by accurately controlling the SCR to the desired inductance.

A. Control Algorithm

The straightforward control strategy would be to sample the output voltage and generate a feedback signal to bias the SCR appropriately and thereby achieves the required equivalent inductance for maintaining the output voltage. A proportional–integral (PI) controller is normally used as the feedback controller. However, because the relationship between the tuning element and the output voltage is bell shaped, it can result in two possible operating points with one being in the over-tuning region and the other in under-tuning region. Moreover using high Q tuning circuits in the power pickups is very advantageous for the IPT systems since the output voltage of the pickup can be boosted to a sufficient level without increasing the track current magnitude or needing more number of turns in the pickup coil windings, which essentially reduces the size and cost of the overall system. But given a high Q circuit, the region of operation cannot be determined apriori and slight detuning can result in significant power drop. Nevertheless, after selecting one of the two operating points of the circuit and defining an operating range, a single-side tuning control method has been proposed [11]. However, with the proposed methods it is difficult to achieve maximum power transfer, and when the operating point shifts to the other region due to circuit parameter variations, it may track in the wrong direction and fail to control the output voltage. The technique proposed in this paper allows the power pickup to achieve full-range tuning/detuning operation to regulate power flow and maintain the output voltage to be constant.

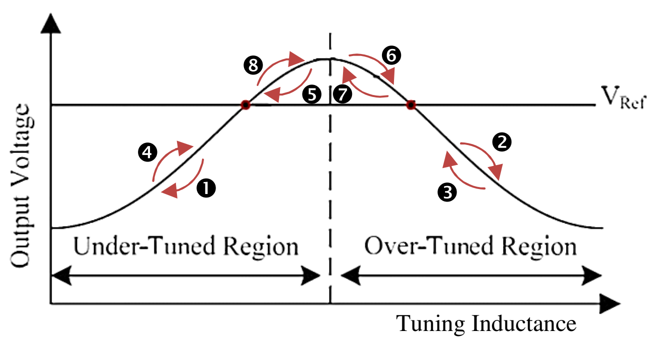


Fig. 9: Relationship between tuning element and pickup output voltage

From Fig 9 it can be observed that there are four regions. By using simple combinatorics it can be deduced that there are 8 states (+ 4 inter region states) in which the tuning circuit can be operating. The region of operation can be determined by knowing present output voltage (above or below V_{ref}) and tuning condition of the circuit (under-tuned or over-tuned). The former can be identified easily with simple comparison (e.g. using comparator). For determining the tuning condition of the circuit presently the different nature of slope in either region of the bell shaped curve can be exploited. Since all direct measurements can be done with respect to time only, the nature of the slope (+ve or –ve) has to be determined indirectly by measuring the output voltage changes with control output changes. Once the region of operation is known the control output can be altered in that direction so as to maintain the output voltage to be constant. The control action is summarized in table 1.

TABLE I
CONTROL MECHANISM

Sr No	Voltage w.r.t. V_{ref}	Change in voltage	Previous Control Action	Tuning Region	Next Control Action
1	Below	Decrease	Decrement	Under	Increment
2	Below	Decrease	Increment	Over	Decrement
3	Below	Increase	Decrement	Over	Decrement
4	Below	Increase	Increment	Under	Increment
5	Above	Decrease	Decrement	Under	Decrement
6	Above	Decrease	Increment	Over	Increment
7	Above	Increase	Decrement	Over	Increment
8	Above	Increase	Increment	Under	Decrement

In states 3, 4, 5 and 6, the output voltage is approaching the desired output voltage. It can, therefore, be inferred that the previous control action was successful in tracking the output voltage to the desired voltage as much as possible. As such, the next control action will replicate the previous one in order to further enhance this tracking. However, if on the other hand, the output voltage is diverging from the desired voltage as in states 1, 2, 7 and 8, the current control action is reversed.

Even in the inter region states, the above control logic does not go into any infinite loop; rather it is able to track back to the reference level. For example if an incremental control action takes the output from under-tuned to over-tuned region with positive change in voltage then next control action would retrace to previous state. But now as the previous control action was to decrement and there was a negative change in voltage, the next control action would be to further decrease the control effort which is indeed the desired action to maintain the output at the reference level. Thus the controller deals successfully with sharp peaks of high Q circuit and sudden jumps from under-tuned region to over-tuned region or vice-versa successfully.

Complete controller layout is shown in Fig 10 and the following control signals are generated to achieve the operation:

1. S_1 to determine whether output voltage is above or below the reference voltage:

$$S_1[n] = \frac{V_o[n] - V_{ref}}{|V_o[n] - V_{ref}|} \quad (12)$$

2. S_2 to determine increase or decrease in the output with the previous control action:

$$S_2[n] = \frac{V_o[n] - V_o[n-1]}{|V_o[n] - V_o[n-1]|} \quad (13)$$

3. With help of above two control signal and previous control action direction, the next control action direction can be determined as:

$$S_4[n] = \overline{S_4[n-1] \oplus (S_1[n] \oplus S_2[n])} \quad (14)$$

The final control output is given by:

$$c[n] = c[n-1] + S_4[n] \times \Delta H[n] \quad (15)$$

$\Delta H[n]$ is a fixed step size, but is reduced to zero when the output is within certain hysteresis band. [In the controller the following Boolean logic mapping is used: -1 implies FALSE and +1 implies TRUE.]

The above control mechanism is motivated from delta modulation (DM) scheme and also possess problems associated with DM, namely Granular noise and slope overload error [12]. The granular noise in the output voltage is result of the fixed step size, which is eliminated in some cases using hysteresis band, but its elimination is not guaranteed. The slope overload error is mainly caused by the slow sampling rate forced by the large time constant of the output pole produced by the filter capacitor of the rectifier. Thus, the output voltage may respond slowly compared to the very fast parameter changes.

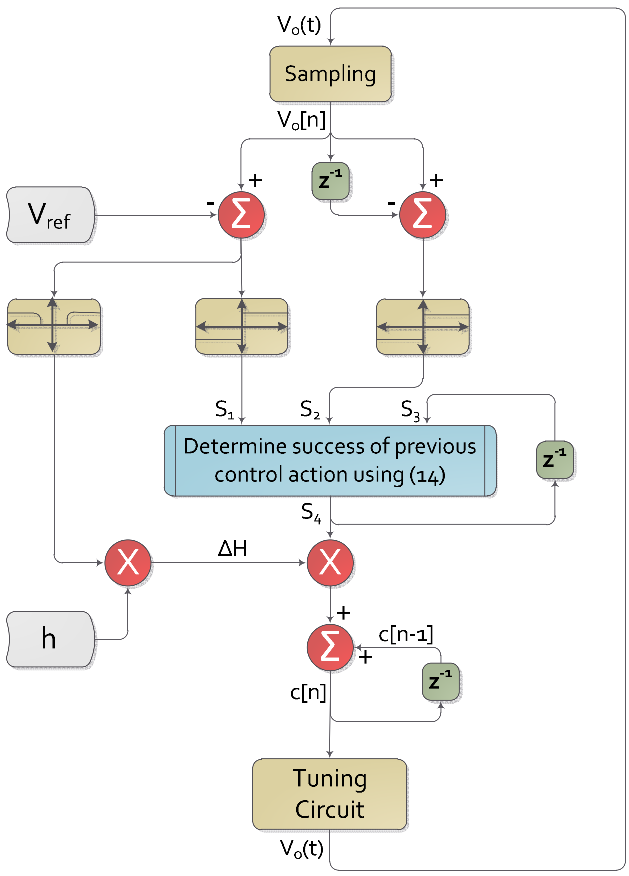


Fig. 10: Complete controller flowchart

B. *Implementation*

The above control algorithm was implemented on Cypress PSoC microcontroller. First the output voltage has to be sampled which is scaled and level shifted appropriately for input to the microcontroller ADC. A software reference is used to represent the desired output voltage. Above control algorithm is programmed in C in the PSoC and other peripherals are interfaced with the main program via software API's. The step size and control output are represented by digital codes with appropriate resolution and will be converted later on into the corresponding analogue voltage by the DAC. The step size code should also be sufficiently large so that any noise present in the control circuit or DAC output is insignificant compared to the corresponding change in the analogue voltage output from the DAC. The control output is fed to the gate of MOSFET, which is used as voltage controlled current source to drive the SCR and thus achieve the required tuning/detuning.

As a microcontroller is used to carry out the control algorithm, the sampling frequency and response time of the controller are therefore critical to determine the control performance of the system.

V. Experimental Results

The proposed ICPT pick-up's performance has been evaluated by delivering power up to 5W to a variable load at 5V for up to 8 mm separation. Table II lists the system parameters.

TABLE II
DEVELOPED PROTOTYPE PARAMETERS

Primary track frequency	38.4 kHz
Primary track current	0.75 A
V_{OC} **variation**	0.63 V_{rms} – 1.2 V_{rms}
Pickup coil inductance, L_{S1}	1.75 µH
Tuning Capacitance, C_{ST}	12.7 µF
C_{S1_0}	9.82 µF
C_{S2_0}	2.88 µF
L_{S2_max}	15.2 µH
L_{S2_0}	5.96 µH
L_{S2_min}	3.71 µH
Quality factor, Q	11.84
Step size	0.1 µH
Rated Output Voltage	5 V DC
Rated Output Power	5 W
Load variation	5 Ω - Open circuit

Practically it has been noticed that when the coupling is such that the induced open circuit voltage in the pick-up coil is under 0.63 V_{rms}, the output voltage would drop below 5 V, and also the pick-up was unable to start under such a condition. It should also be noted that when the power pickup is over-coupled (deliberately by increasing primary track current) the output voltage fails to regulate at 5 V. For example when the open circuit voltage of the pick-up coil is 1.5 V, then the output voltage increases to 6.1 V, which is beyond the maximum tuning range of the designed controller.

Fig 11 shows the output voltage of the pick-up under rated conditions, the granular ripple of 440 $mV_{p\text{-}p}$ is clearly visible. This ripple can be reduced by implementing adaptive step size.

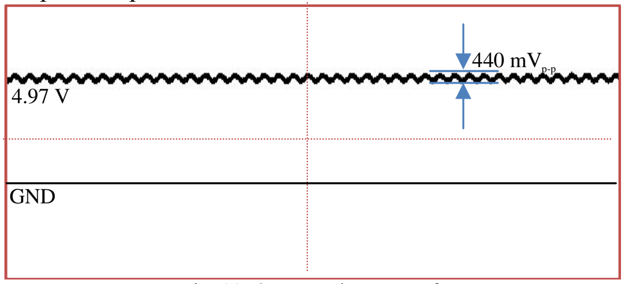


Fig. 11: Output voltage waveform

VI. Conclusions

A linearly tuned contactless power pickup has been developed and implemented successfully. It has been tested by delivering 5W at 5V to the load with good results. The proposed technique allowed the power pickup to achieve full-range tuning/detuning operation to regulate the power flow and maintain the average output voltage to be constant. Thus the primary track current can be greatly reduced to minimize track losses, and unwanted coupling with metallic objects. The proposed technique can be a viable alternative to other power pickup control methods.

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