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RIPPLE CORRELATION CONTROL

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ABSTRACT : *This paper extends the previous analog technique to the digital domain. Ripple correlation control (RCC) is a high-performance real-time optimization technique that has been applied to photovoltaic maximum power point tracking. First, the general DRCC method is derived and stability is proven. Then, DRCC is applied to the photovoltaic maximum power point tracking problem. With a few simplifications, the RCC method is reduced to a sampling problem; that is, if the appropriate variables are sampled at the correct times, the discrete-time RCC (DRCC) algorithm can quickly find the optimal operating point. Experimental results verify tracking accuracy greater than 98% with an update rate greater than 1 kHz. The proposed digital implementation is less expensive, more flexible, and more robust.*

1. INTRODUCTION

The online identification of the optimum operating point and the development of a corresponding control system which enables the nonlinear system to robustly operate at such a point constitute an important challenge. In the design of these control systems that desirably maintain these corresponding nonlinear systems operating at or near their optimum operating point, power electronics circuits and systems have been implemented. Most power sources and loads are nonlinear systems and have an optimum operating point Typically, power electronic circuits and systems manipulate energy flows of power sources and loads with switches. Consequently, switching power converters are also nonlinear large-signal systems.[1]

Ripple has typically not been considered as a source of information, and numerous techniques have been configured to minimize ripple and discontinuities of switching by smoothing out the switch actions and averaging through filters. Switching actions produce ripple, which cannot be avoided without a power loss penalty. In many power converters and their controls, ripple is at best a substitute for a switching control (as in hysteresis control) and at worst a nuisance and a source of noise and interference.

Research results have shown that significant control objectives, such as cost function optimization, can be addressed with a ripple correlation technique. Ripple correlation control (RCC) has opened a whole suite of new possibilities for converter action and for control loops. However, ripple which is inherent to the switching actions and represents a consistent perturbation signal has been found to be a source of information and a basis for control.

Typical applications have included active maximization of converter efficiency and other nonlinear functions. RCC is a nonlinear control approach applicable to power electronic circuits, which makes use of voltage, current, or power ripple and correlates the ripple with switching functions to effect control, has been shown to directly support cost- function minimization and maximization, and can be applied RCC has also been applied to adaptive dead time adjustment, solar power processing, and motor power minimization. Among these typical applications figure solar panels, which can deliver maximum power at a particular voltage and current point that varies with the temperature and illumination affecting the solar panels? Nearly all recent work on MPPT approaches involves power electronics to implement the solutions.

These have been developing different maximum power point tracker (MPPT) methods to operate solar panels at their maximum operating points or levels. Energy processing for solar panels is generally done with modern power electronics, because switching power converters as designed for power electronics applications offer high efficiency and are readily controlled.

Moreover, while RCC is a general method for optimization method, its application to the solar MPPT problem is well established. Tracking the maximum power point is extremely important for solar applications. While the price of solar panels has dropped dramatically over the past 30 years, solar panel size and cost are dominant factors in a solar installation. In the most basic installations, solar panels are connected directly to a battery through a diode, which forces the panels to operate at a voltage that follows the battery characteristics, not the panel characteristics, and does not deliver maximum power. More sophisticated applications use a switching power converter to interface between the solar panel and the load. When a switching power converter is present, RCC represents a minor addition to the converter control to achieve tracking of the panel maximum power with minimum extra cost.

RCC has previously been cast as a continuous-time technique, implemented with analog circuits. Many applications can benefit from an RCC technique that provides reduced quiescent power and mode-switching However, the continuous- time technique of the RCC typically requires that the controller operates with a substantially high volume of information and a correspondingly high sampling rate, which may be problematic.

These and other needs will become apparent to those of skill in the art after reading the present specification. Therefore, a need exists for a ripple correlation control that operates a switching power converter at optimum conditions with a low sampling rate that overcomes the problems noted above and others previously experienced for addressing issues of volume of information, reduced quiescent power or mode-switching.

Systems consistent with the present invention provide a ripple correlation control that operates a switching power converter at optimum conditions with a low sampling rate.

The fore going problems are solved and a technical advance is achieved by the present invention. A method for controlling a variable of a switching electrical circuit detects values for each of and at a predetermined instant during a switching interval of a switching operation of the electrical circuit, both of the first and second waveforms are perturbed by the switching operation, and evaluates the variable based on the corresponding

The method further adjusts an operating point of the circuit based on a change in the variable between the two evaluations so as to minimize the change in the variable. Here consistent with the present invention also provide a method for controlling an input power to a switching dc-dc converter. The method senses a first ripple on an input voltage to the converter; the first ripple is produced by a switching operation of the converter, and detects values of the input voltage at a beginning of and at a predetermined instant during a switching interval of the switching operation of the electrical circuit. The method also senses a second ripple on an input current to the converter; the second ripple is produced by the switching operation of the converter, and detects values of the input current at the beginning of and at the predetermined instant during the switching interval. The method evaluates the input power based on the corresponding values of both the input voltage and the input current detected at the beginning and at the predetermined instant during the switching interval, and varies a duty ratio of the switching operation based on a change in the input power so as to minimize the change in the variable... The experimental converter is applied to an MPPT application for a PV panel, so the development that the objective is to choose a cost function representative of panel power and maximize. RCC uses switching ripple to optimize a cost function that is a function of a state variable. An equivalent formulation can be developed to minimize a cost function, as in efficiency maximization (power loss minimization), with a sign change. Global stability requires that is unimodal, that is, there is a single global maximum. In a practical solar application, local shading can create multiple peaks, and the mode-switching method can increase the likelihood that the global maximum is achieved.

For a suitable cost function, the maximum value occurs where

$$dJ/dz = 0 \qquad (1.1)$$

The power conversion plant has an input (such as the duty ratio in a dc-dc converter). Just as must be unimodal, the steady- state value

$$\Psi(u)=\lim_{t\to\infty} z(u,t) \qquad (1.2)$$

must be monotonic over the operating range. Monotonicity ensures that there is no polarity inversion in the system gain, and may be satisfied by limits on or by a coordinate transformation. An integral control law

$$u= k \int(dJ/dZ)dt \qquad (1.3)$$

will drive the operating point to the maximum value of . The sign of and the effect of on determine whether the control law goes towards a maximum or a minimum. The magnitude of influences convergence rate. Usually, derivatives like are unavailable in a practical system, so a more useful controller is needed. If the integrand is multiplied by a positive value, the equilibrium operating point does not change. A convenient multiplier is , which by the chain rule yields

$$u= k\int (dJ/dZ)(dZ/dt) (dZ/dt)dt$$
$$= k\int (dJ/dZ)(dZ/dt) dt \qquad (1.4)$$

This control law only needs time derivatives, likely to be readily available in a real system. The transformation is possible if positive value, then a negative value. Over a time interval from 0 to "I"

Here,T is the switching period and is the fraction of the period when , which may or may not be the same as the duty ratio of a controlled switch. Both and may vary, so long as neither goes to zero and does not go to 1. A definite integral etermines the change in over a single period. The period can be subdivided according to the value of and the definite integral can be evaluated symbolically

$$\dot{z} = \begin{cases} w_+ & \mathrm{mod}(t,T) \in [0, DT) \\ w_- & \mathrm{mod}(t,T) \in [DT, T) \end{cases} \qquad (1.5)$$

This result can be generalized to any switching period that is ligned with the minimum of the rising edge. If a periodic steady-state condition is possible, it would require these relationships can be substituted into give a control law. Just as many approximations have been proposed for the analog RCC law, here are possible simplifications. Instead of using a gain on the difference between samples of, use a gain on the of the difference.

2. DRCC

2.1 DRCC(Direct ripple correlation control)

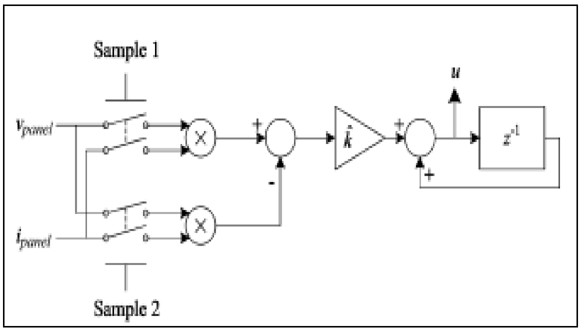

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Fig. 2.1 Block diagram of DRCC sampling process

Although the DRCC control law superficially resembles a conventional perturb-and-observe (P&O) process for optimum tracking , there are at least two primary differences. First, the time scale is far different. The P&O technique uses two samples of output power that correspond to two steady-state operating points. When the operating point is adjusted under a P&O method, the system must wait for all transients to settle before recording information. In contrast, DRCC uses a pair of samples within a single switching period. The update rate can be as fast as the witching frequency, with suitable choices of the microcontroller and analog-to-digital converter (ADC) system. [3]

P&O always exhibits sub harmonics (large-signal operating point ripple at a fraction of the MPPT update rate), whereas DRCC achieves true equilibrium. P&O always leaves the present operating point to determine whether the optimum is nearby. It does not fully converge, in the sense that the operating point must be adjusted on a continuing basis. DRCC uses information in the ripple at a given operating point to determine whether equilibrium has been reached, and will in fact converge to a specific duty ratio, altering it automatically if a parameter changes.

When the switch is turned off, this energy is fed to the load and the output capacitor through the diode. Typical boost converters include a capacitor and a switch connected in parallel with a source, an inductor connected between the source and the switch and a diode connected between the switch and the capacitor. When the switch is turned on, the inductor stores energy from the source. The energy stored in the capacitor provides the load power when the switch is turned on. As such, the output voltage obtained is higher than the input voltage by a factor of 1/ (1-D), where D is the duty ratio of the switch. By incorporating the DRCC controller the source converter becomes a variable dc-dc converter that uses a digital ripple correlation control algorithm to force the terminals of the photovoltaic panel to an impedance that produces the maximum power out of the panel of the energy source. The DRCC is configured to adjust the panel operating point to extract maximum power on a moment-by-moment basis. As such, the source converter does not disrupt voltage level or interfere with voltage regulation action elsewhere in the power supply apparatus. The DRCC controller may act entirely based on panel terminal characteristics so as to function irrespectively of the voltage at node. The DRCC controller may also be configured to enforce a voltage limit and permit an external digital command to shut it down. Without such a limit or command, excess solar power may continue to be delivered from the energy source unit even when the load is light. In this situation, solar energy is not needed, and there is a potential for delivering excessive voltage at the output node. Moreover, when the produced energy falls below a predetermined energy level, the DRCC controller may deactivate the source converter. Power tracking subject to a voltage limit and shutdown command is a known practice.

Like many optimization algorithms, RCC finds a local extremum. There are two basic limitations on the use of RCC. This is not a problem for a single solar cell, but can be a challenge for complicated interconnected panels. Limits can be enforced to ensure that the local extremum is in fact the global extremum. In many cases, this is a simple task that can be enforced with limits on the input command u (t). Second, RCC can make use of phase information, so any unmodeled dynamics that alter the phases of signals will enter into J or z and could interfere with the action of the MPPT. Limitations owing to unmodelled dynamics often drive design decisions, such as the choice of z.

Beyond these basic limitations, there is a significant barrier to implementing RCC in an analog circuit. While analog multipliers exist, they are not common and tend to be relatively expensive and power hungry compared to more common analog circuits. This is a significant advantage, since synchronous demodulators are common and inexpensive. In solar power applications, computation of J usually involves a second multiplication. For example, the solar panel power P_{pam}ι is the product of v_{pane}\(t) and i_{pan}ei(0- This step is less suited for a synchronous demodulator, so the drawbacks of analog multipliers remain. If these two limitations can be overcome, RCC provides excellent power tracking.

Many of the limitations of the continuous-time RCC can be minimized if the controller were implemented digitally. For example, mode-switching can be used to ensure operation near a global extreme. Microcontrollers with hardware multipliers are available at a variety of price points. An obvious implementation is to sample all of the signals necessary to compute J and z at a high sampling rate and implement Equation directly. Further, the problematic high sampling can be mitigated by determining signals that can be sampled at a modest frequency such as f_{sw} or $2f_{sw}$ then used in a digital computation to provide a useful approximation.

To develop this alternative approach, the internal state variable z (t) that represents a voltage or current within the switching power converter is utilized. Let us assume that the time derivative z (t) does not change sign more than once per period. In a typical dc-dc power converter, a change in sign of the time derivative is governed by switch action and therefore occurs once per switching cycle. As such, a time fraction when z > 0, denoted as D, is determined and the time reference t is set at 0 at a moment when z becomes positive. Define
As such, a simplified process with reduced sampling requirements follows directly from
1. Sample the variables that affect J at the beginning of the interval T and at the instant when z changes sign;
2. Compute J from the sampled variables; and
3. Adjust based on the change in J between samples.
Thus, the input command u can be updated once each period based on two samples of the variables or twice each period if samples are taken during both intervals: once at (or just after) the beginning of the period, once in the middle (at DT) and once at (or just before) the end of the period. In order to reduce computational and sampling burdens, the input command u can be held constant for some time nT_{sw} after which the controller samples and evaluates J. To further reduce computations, simplifications can be made. For example, Moreover, the sign of the difference (J(DT) -J(O)) can be used instead of the actual difference, which can represent a delta modulation. Then in the simplest form, the result is
u (T) = u (0) + k sgn (j(DT) -J (O)) (2.1)
This process continues to change the control or input command u(t) until
J (DT) = J(θ) , (2.2)
which would indicate that the cost function J is no longer changing on average and an optimum has been reached. Further, J is the same at the beginning, middle, and end of the switching interval T and is at an extreme. It is important to notice that the special times 0 and DT are not unique. Samples taken at somewhat different intervals such as O+Δt and DT+ At can also be used to achieve the same result. Off-nominal times at worst will drive operation only slightly away from the desired optimum, since ripple should not be large and the possible error in this case does not exceed the ripple level. In addition, while periodic operation is typical, for this control, interval T need not be constant. It is only necessary to be able to determine T as the converter operates.[4]
Any converter that presents a constant output current to the panel terminals may be used. While RCC has been successfully used in solar MPPTs, a digital version of an RCC (DRCC) may be advantageous. A convenient choice can be a boost converter,Define
J (X) = ^{P} panel (0 = Ï pane, (Φ panel (0 z(0 = W,(0
Equation 10 u = D)
In the boost converter, z = - q , where q is a command to the gate of the

di_{panel}/dt controlled switch. A microcontroller is used to generate q with uniform PWM. Conventional sensors detect $ipa_{ne}i(t)$ and $v_{pane}\iota(t)$, then an analog-to-digital converter (ADC) (not shown) synchronized to a PWM process samples the sensor outputs at the two edges of q.

2.2 MPTT methods:-

There are nine MPTT methods. They are given below
1) P & O (Perturbation & observation)
2) Increment conductance.
3) Fractional open circuit voltage.
4) Fractional short circuit current.
5) Neural network.
6)Fuzzy logic control.
7) Ripple correlation control.
8) Current sweep.
9) DC link capacitance voltage.

P&O Involves a perturbation in the operating voltage of the PV array. The process is repeated periodically until the MPP is reached. The system then oscillates around the MPP. The Oscillation can be minimized by reducing the perturbation. The MPP can thus be tracked by comparing the instantaneous conductance (I/V) to the Incremental conductance (ΔI/ΔV). Vref is the reference voltage at which the PV array is forced to operate.
Fast tracking can be achieved with bigger increments but the system might not operate .Once the MPP is reached, the operation of the PV array is maintained at this point unless change in ΔI is noted, indicating a change in atmospheric conditions and the MPP. Exactly at the MPP and oscillate about it instead; so we need a tradeoff. The increment Size determines how fast the MPP is tracked.
Microcontrollers have made using fuzzy logic control popular for MPPT over the last decade. Fuzzy logic control generally consists of three stages:
1. Fuzzification.
2. Rule base table .
3. Defuzzification .
Along with fuzzy logic controllers came another technique of implementing MPPT-neural networks, which are also well adapted for microcontrollers. Neural networks commonly have three layers:
1. Input layer
2. Hidden layer
3. Output layer
When a PV array is connected to a power converter, the switching action of the power Converter imposes voltage and current ripple on the PV array. Ripple correlation control (RCC) makes use of ripple to perform MPPT.[5]
RCC correlates time derivative of time varying PV array power with time derivative of PV array current or voltage to drive the power gradient to zero. The derivatives are usually undesirable, but ac-coupled measurements of the PV array current and voltage can be used since they contain the necessary phase information.

2.3 DRCC stability

The stability of continuous-time RCC was proven in but a new stability proof is needed for the much simpler DRCC process. There are two aspects to prove: first, that the equilibrium corresponds to the optimum, and second, that the control law will cause the operating point to converge to this equilibrium. The proof below will consider only the maximization problem, since minimization can be achieved with a sign change on the gain .A few assumptions and definitions are necessary. Assume that the plant has an average model

$$\frac{dz}{dt} = f(z, u). \quad (2.3)$$

The average-model state variable can be related to the physical state variable with an algebraic ripple correction function,

$$x(t) = z(t) + \psi(u, t).$$

$$x(t) = z(t) + \psi(u, t). \quad (2.4)$$

Although the variable names and terminology are different, The ripple is small relative to x and z) with zero mean over a switching period. (x And z) with zero mean over a switching period. Assume also that the dynamical system has an equilibrium at

$$z = \varphi(u). \quad (2.5)$$

The input is constrained such that the equilibrium function must be monotonic on this interval. The cost function is summed to be unimodal, with a unique maximum.

The time-based approach enhances noise immunity, since the extremes of the voltage ripple can be quite rounded while the switching edges are known exactly. All solar panels have capacitance that results from stored charge at the p-n junctions. Known results have proved that choosing z(t) =v_{pane}ι(t) greatly reduces the effect of panel capacitance on the correlator compared to the choice z(t) = i_{pane}ι(0. The designer may choose to compare the derivative oïv$_{pane}$ι(t) to zero with an analog circuit to sample precisely when z changes sign. An alternative is to estimate the phase delay between the gate command and the voltage extremes, which occur when z changes sign. The amount of delay varies with the panel time constant (incremental resistance multiplied by small-signal capacitance).

To find the sampling times the differential equation governing the energy source current and voltage can be solved explicitly. By neglecting dc components, the inductor current is an asymmetric triangle wave. The energy source unit 10 can be dV modeled as a resistance R = 40 in parallel with a capacitance C 42 related to stored charge at the pn junction, as shown in for a small-signal equivalent circuit. The differential equations can be solved to find v_{pmel} (t) . The correct sampling times occur when $^{pa"d}$ (t_{sample}) = 0 .

The total tracking effectiveness is less than 100% with mode switching, although it is more than 99% if $T_3 > 100T_2$. This tracking effectiveness is much higher than with CVF alone and avoids the local extremum challenge of prior RCC implementations[7]

An example of the MPPT18 incorporating the DRCC controller was built to verify the DRCC technique. The solar panel or energy source unit has a total area of 0.5 m^2 comprising 18 cells in series, for an open-circuit voltage of 12 V and a short-circuit current of 7.5 A. The source converter controlled with MPPT 18 uses a boost topology. The inductor is 5 niH, built on a high-flux toroid core. The controlled switch is a FDR6580 MOSFET from Fairchild Semiconductor; the Schottky diode 24 is a S 15L45C from STMicroelectronics.

Lower power techniques were used throughout the design to accommodate minimum insolation. Unused peripherals are disabled. Where high speed operational amplifiers (op amps) are needed, the LM6142 from TI is used. Where low speed op-amps are needed, the OPA4348 from TI is used instead to reduce quiescent current. The main controller is an MSP430F148 from Texas Instruments (TI) Outputs from the microcontroller synchronized to but delayed from the PWM waveform, drive 74AHC4066 analog (2.5) switches in a sample-and-hold circuit to sample panel voltage.

In general, if the insolation is high, ample power is available and tracking effectiveness is less critical. This exemplary embodiment of the MPPT was designed for a remote unattended power source. A key to success is extracting maximum power at low insolation. This was tested with the energy source unit or panel 10 under a fluorescent light fixture.. First, the panel goes to its open circuit voltage V_{oc}, which varies with temperature and insolation. Next, the CVF controller (not shown) is enabled. The duty cycle increments until the panel reaches $k_{cv}fV_{0C}$ in about 60 ms. .The DRCC controller 20 is enabled to find the exact optimum. Since $k_{cv}fV_{0C}$ is near the maximum power point already, convergence of the DRCC controller 20 takes place in only 30 ms. Noise in the oscilloscope current measurement affects the offline computed power, but still, a 3% power increase can be measured between CVF and DRCC operation.

Accordingly, the present invention is not to be restricted except in light of the attached claims and their equivalents. While various embodiments of the present invention have been described, it will be apparent to those of skill in the art that many more embodiments and implementations are possible that are within the scope of this invention.

3. RCC

3.1 Block diagram of RCC

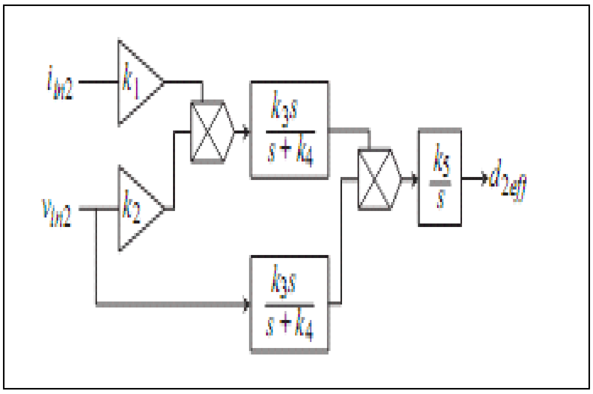

Fig 3.1 Block diagram of RCC

3.2 Explanation of block diagram

Based on which goes through most of the existing MPPT techniques, RCC better suits our application, not only because of its ability to track the true MPP of the PV array, but also because of its simple analog implementation and incorporation in the MIBB. The measured current-voltage (I-V) and power-voltage (P-V) curves of the PV array used for the experiment. These curves were obtained at full irradiance. Since the incremental cost of solar energy is very low, it makes sense to use the maximum power out of the PV array and use the smallest fraction of the secondary source only to and use the smallest fraction of the secondary source only to meet the load requirement. The shapes are typical of PV arrays at any irradiance level. The P-V curve shows that there is a unique global MPP at P_{MPP}. According if the time-varying PV array voltage v or current i is increasing (v > 0) or Output Voltage Regulator simple voltage proportional integral (PI) control shown was used to regulate the output voltage. The duty cycle d_{1eff} of the line source was used to supplement the power of the PV array, providing sufficient output power for the desired output voltage. This control method only works when the available power of the PV array is less than the desired output power. If the PV array power exceeds the output power, the output voltage will exceed the reference V_{ref} due to the RCC. If the output voltage were tobe regulated under this condition, the control strategy would need to be changed, which would be easier to implement in a microcontroller than in an analog circuit.[9]

3.3 Discrete-time formulation

A digital version of RCC is preferable for many reasons. While analog multipliers tend to be power-hungry, low-power microcontrollers are available with hardware digital multipliers. For example, an MSP430F148 has a hardware bit multiplier, and the total microprocessor core consumes less than 2.5 mW. A digital implementation enables other features, too, such as protection modes and user interfaces. While the analog control law could be converted to discrete time with fast sampling, e.g., ten or more samples per switching period, and a suitable high-end microcontroller or DSP, the application of general waveform knowledge yields a simpler control law. In dc-dc converter applications, is piece wise linear, so its time derivative is piecewise constant.

At equilibrium, oscillates around the maximum at twice the switching frequency and reaches the same value at each end of the oscillation when the state variable is at a maximum and when is at a minimum.. The sampling process is shown in Figs. 3.2 and 3.3 for an MPPT. The generic cost function is implemented as, the panel power. The state variable is chosen as, the panel current. Panel voltage is also sampled to allow computation. In Fig.3.2, the panel is at the maximum power point. The panel is not at the maximum power point current needs to increase. The instantaneous power passes through the maximum twice in each switching cycle, once while the current is increasing and once while the current is decreasing. The average delivered power is essentially as high as possible in Fig. 3.2, limited only by the converter ripple.[10]

4.CONCLUSION

4.1 Conclusions

In the same time, at the initial design stage level all the parameters and the limitations are not totally finalized; some of them could be modified during the subsequent stages of the design, even during the practical determination. If the parameters could be a little different, the operating modality and the behavior of the system remain the same.

We can observe that the input filter and the line filter for the intermediate circuit significantly reduced the electromagnetic interferences. By analyzing the simulated and the experimental results, one can notice than they are similar, with small differences caused by the exploitation conditions that could not be simulated in their total amount.

The new equipment has the advantages that it eliminates the shocks corresponding to start, stop and speed regulation regimes, directly influencing the travelers' comfort. This mean an important improvement in the electromagnetic compatibility.Now the modernized vehicle is under exploitation. Its monitoring continues in order to define exactly the reliability indicators and the maintenance program.[11]

4.2 Advantages

More sophisticated applications use a switching power converter to interface between the solar panel and the load. When a switching power converter is present, RCC represents a minor addition to the converter control to achieve tracking of the panel maximum power with minimum extra cost.

4.3 Application

The perturbations are normally due to ripple that is naturally present in electric drive systems. In the steady state, the fast-average value of the independent variable converges asymptotically to a point no more than the magnitude or the ripple away from the optimum set point. Ripple correlation control can be applied to electric drive systems in order to optimize some cost function independent of parameters. This involves correlating the perturbations in the cost function with the perturbations in the independent variable to obtain a command for the independent variableIn certain applications, cost function observers must be created to obtain the correct correlation information. In this paper, ripple correlation control is developed and demonstrated for DC, induction, and brushless DC drives

Time and frequency domain simulations in MATLAB/Simulink verify the feasibility of such an application and show promising results in energy savings. Here, output power maximization of a regenerative braking system using ripple correlation control (RCC). The proposed RCC application thus leads to a reduction in the size of the battery pack in an electric vehicle. Results show that the proposed optimization can increase regenerated power by up to 20% compared to conventional regenerative braking systems. Ripple correlation control is a nonlinear control approach applicable to power electronic circuits. It makes use of voltage, current, or power ripple and correlates this with switching functions to effect control. The technique is especially well suited to power electronics because ripple is inherent, and can be treated as an internal perturbation. Ripple correlation control directly supports cost-function minimization and maximization. It can be applied, for example, to dynamic power optimization. It has been applied to adaptive dead time adjustment, solar power processing, and motor power minimization. Potential future applications include active maximization of converter efficiency and other nonlinear functions

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