

DIMMABLE LIGHTING SYSTEM

FIELD OF THE INVENTION

This invention relates to apparatus and methods for
5 providing (1) high power quality and (2) dimming control for
individual electrical lamps or more generally electrical
lighting systems including systems formed by a plurality of
individual lamps. The invention relates in particular to a
simple general purpose and non-intrusive dimming system that
10 can be retro-fitted to existing lamps and which is non-
intrusive in the sense that when not in use the dimming
apparatus has no effect on the normal operation of the lamp.
The apparatus and dimming methods maintain high power
quality (with capability up to unity input power factor)
15 from the power system at any dimmed power level.

BACKGROUND OF THE INVENTION

A wide range of different types of lamps and lighting
systems are used in various applications. These include
20 incandescent lamps, fluorescent lamps, high- and low-
pressure discharge lamps. For both aesthetic and energy
saving reasons, various attempts have been made in the prior
art to provide such lamps with a dimming control so that the
brightness of the lamps can be adjustable.

25 Dimming function is particularly useful for high
intensity discharge (HID) lamps, which are widely used in
public lighting systems due to the HID lamps' manifold
advantages such as longevity and high luminous
efficacy. Unlike incandescent lamps, high intensity
30 discharge lamps generally require a long warm up time to
reach full brightness. After being shut off, they need a
cooling down period before they can be restarted again. It

is this "re-strike" characteristic that makes dimming a very attractive alternative to simply turning the lights off, because dimming does not require the turning off the lamps and can therefore avoid considerable warm-up time of the lamps after re-ignition. Although numerous attempts have been made in the prior art to develop dimmable electronic ballasts for individual lamps, conventional magnetic ballasts are still the most reliable, robust, cost-effective, and dominant choice for high-wattage discharge lamps and large-scale lighting systems, such as street lighting systems.

Dimming also has other advantages such as reduction of peak power demand, increase of flexibility for multi-use spaces, safer driving in light traffic conditions and avoidance of light pollution. This invention relates to a dimming technology that can dim a lighting system formed by a plurality of lamps. Existing non-dimmable lighting infrastructure can be converted into a dimmable one with real energy saving. No major change of the lighting electrical network is needed. Of particular importance, the technology will maintain the principle of providing "environmentally clean" power conversion that will not introduce harmonic pollution problem into the power system.

PRIOR ART

Existing dimming methods for existing lighting systems include Triac-based dimmers for incandescent lamps and gaseous discharge lamps compatible with triac dimmers, dimmable electronic ballasts for gaseous lamps, and a range of disparate techniques for dimming lamps driven by magnetic ballasts. These prior art techniques will be discussed in turn.

Triac-based dimmers have been popularly used as the dimming devices for Edison-type incandescent lamps and some triac-dimmable fluorescent lamps [1]. The circuit connection is illustrated in Fig. 1(a). A triac dimmer consists of a triac and also a triggering circuit which controls the phase angle of turning the triac on over a cycle of the mains voltage. As shown in Fig. 1(b), by controlling the delay angle (α), the output root-mean-square voltage, and thus the power to the lamp, can be controlled. This control of ac voltage results in the ability to adjust the brightness of the lamp.

However, the waveshape of the mains input current through the triac dimmer is dependent on the delay angle. When the delay angle is nonzero, the input current will deviate from the sinusoidal shape of the mains voltage. When the delay angle is increased, the conduction time of the triac is diminished. The input current will then consist of high harmonic components and thus generates undesirable harmonics into the power system. In addition, as the input power factor is the product of the displacement factor and the distortion factor [2], the input power factor becomes small when the delay angle is large. It is because the displacement factor is equal to the cosine of the delay angle (If the delay angle is large, the displacement factor will become small.) and the distortion factor deteriorates as the current harmonic content increases. The ultimate effect of this low input power factor is the presence of reactive power flow between the ac mains and the lighting system. This reactive power could cause serious defects over the power system. The lower the power factor, the larger the rating of the transformers and the larger the size of the conductors of transmission must be. In other

words, the greater the cost of generation and transmission will be. That is the reason why supply undertakings always stress upon the consumers to increase the power factor [3].

Recently, there has been an increasing trend of using
5 dimmable electronic ballasts for discharge lamps such as
fluorescent lamps and high intensity discharge (HID) lamps.
A dimmable electronic ballast usually has a 4-wired
connection arrangement on the input side. Two connections
are for the "live" and "neutral" of the ac mains, the other
10 two are for the dimming level control signal, which is
typically a dc signal within 1V-10V. A general structure of
the dimmable electronic ballast is illustrated in Fig. 2(a).
It consists of an active or a passive power factor
correction circuit, a high-frequency dc/ac converter, and a
15 resonant tank circuit. The power factor correction circuit
and the dc/ac converter are interconnected through a dc link
of high voltage. The dc/ac converter is used to drive the
lamp through the resonant tank circuit. It is usually
switched at a frequency slightly higher than the resonant
20 frequency of the resonant tank circuit. The resonant tank is
used to provide a high voltage to ignite the lamp and
ballast the lamp current. Dimming function is achieved by
controlling the dc link voltage and/or the switching
frequency of the dc/ac converter. The input power factor can
25 be kept high at any power level. As illustrated in Fig. 2(b),
the waveform of the input current i_{ac} is sinusoidal and in
phase with the ac mains.

A typical circuit of electronic ballast for fluorescent
lamps is illustrated in Fig. 2(c), in which the ac mains is
30 rectified by a rectifier, the power factor correction
circuit is realized by a boost dc/dc converter, the dc/ac
converter is realized by a half-bridge inverter circuit, and

the resonant tank circuit is formed by L_r and C_r . The dc link voltage is regulated at a level slightly higher than the peak value of the ac mains voltage. If the lamp is dimmed by increasing the switching frequency of S_1 and S_2 ,
5 then the reactance of L_r is increased, so that the power delivered to the lamp is reduced.

Electronic ballasts for fluorescent lamps (low-pressure discharge lamps) have been widely used and have been shown that their use has an overall economic benefit [4].

10 Operating at high frequency (typically above 20-kHz) electronic ballasts can eliminate the flickering effects of the fluorescent lamps and achieve a higher efficacy than mains-frequency (50Hz or 60Hz) operated magnetic ballasts. Therefore fluorescent lamps driven by electronic ballasts
15 consume less energy for the same light output when compared with lamps driven by magnetic ballasts. However, one major weakness of electronic ballasts is the relatively short lifetime (typically less than 3 to 5 years for high-quality products). Magnetic ballasts can normally operate over 10
20 years without replacement and it is rare to have electronic ballasts with such long lifetime. Also, the inductor core materials and winding materials are recyclable, while electronic ballasts have more toxic and non-recyclable materials.

25 In HID lamps market, the situation of using electronic ballasts is different. Electronic ballasts are only used in a minority of mainstream HID applications. They are limited to small-scale systems and consumer products, such as projectors, film lighting, and automobile headlamps [5]. One
30 main reason is that HID lamps could suffer from *acoustic resonance* when they are operated at high frequency. Acoustic resonance is due to the power pressure variation in the lamp

tube that could trigger various forms of resonance - as occurring in the woodwind musical instruments. In principle, it can be avoided by operating the lamps at a low frequency (< 1kHz) or a very high frequency (> 350kHz - 700kHz) [5, 6].

5 However, the lamp characteristics change with time and thus lamp stability is not guaranteed when the lamp's ageing effects become crucial. Unlike incandescent lamps, HID lamps require a long warm up time to reach full brightness. After being shut off, they need a cooling down period before they
10 can be restarted again. It is this "re-strike" characteristic that makes dimming a very attractive alternative to simply turning the lights off - in order to avoid spending considerable time waiting for the lamp to warm up. Dimming also has other advantages such as energy
15 saving, esthetic purpose, increase of flexibility for multi-use spaces, safer driving in light traffic conditions [2] and reduction of light pollution in outdoor lighting systems. Hence, despite the increasing efforts on developing electronic ballasts, conventional magnetic ballasts are
20 still the dominant choice, especially in outdoor applications. Unlike electronic ballasts, magnetic ballasts have the advantages of extremely high reliability and long lifetime, and robustness against transient voltage surge (e.g. due to lightning) and hostile working environment (e.g.
25 high humidity and wide variation of temperature). Particularly, they offer superior lamp-arc stability performance in HID lamps. In the past, the major limitation of magnetic ballasts was their lack of flexibility in achieving dimming control.

30 Apart from the technical issues, it is also not economical to use a dimming device for each individual lamp in a lighting system formed of a large group or network of

lamps. The arrangement is particularly a concern for converting a non-dimmable lighting system into a dimmable one by replacing all dimmable control gears with dimmable devices. As illustrated in Fig. 3, the wiring and electrical installation will be complicated, since it is necessary to redesign the electrical networks for both power lines and control signals. The situation will be even more complicated in systems having multiple zones. Therefore, installation of individual dimmable electronic ballasts in all lamp posts in a road lighting system, for example, will involve high installation cost and will also be a maintenance nightmare for the road lighting management companies, in view of the relatively poor immunity of electronic ballasts against extreme weather conditions.

Therefore, if magnetic ballasts can be made dimmable, the combined features of their long lifetime, high reliability and energy saving can make such "dimmable magnetic ballasts" an attractive solution for both indoor and outdoor applications. Moreover, it would be useful to have a technology that can dim a plurality of lamps with magnetic ballasts. Fig 4(a) shows the general non-dimmable lamp system configuration with magnetic ballasts, in which the input of the ballasts is directly connected to the ac mains through a switch gear. The switch gear is used to turn on the lamps and is controlled by various means, for example, manual control, automatic timer control, and photo-sensor. To date several dimming methods for lamps with magnetic ballasts have been reported. The ultimate purpose is to control the lamp current, and hence the lamp power, so that the lamps' brightness can be varied. The strategies are mainly acted on the input side of the ballast or at the lamp

side. As depicted in Fig. 4(b), they can be categorized into several methods.

Method I - Control of the supply voltage or current to the lamp

Reducing the voltage supplying to the ballast is a direct way of dimming. As illustrated in Fig. 4(b), when the supply voltage v_L is reduced, the supply current i_L , the lamp current i_{Lamp} , and hence, the lamp power will be decreased. This method can be realized by various voltage transformation means, such as low-frequency transformers or high-frequency switching converters.

One of the most obvious methods of altering the voltage conditions on the ballast input is to provide means whereby the voltage ratio of the supply transformers in the system may be varied. As the voltage ratio is dependent on the turns ratio, it follows that if the turns ratio can be altered then the voltage ratio will be changed by the same amount [5]. Various methods have been adopted for effecting this desired change in the transformation ratio, the most simple one involving the use of a tapped winding on one side of the transformer, so that the effective turns-ratio can be altered. Another one is the use of autotransformer that the turn-ratio can be continuously varied. In [7], a two-winding autotransformer is used to provide two voltage levels for implementing a two-level dimming system. In [8], a multilevel dimming system that uses a more complicated transformer is proposed. All these methods involve the use of mechanical devices, such as contactors for changing the turns-ratio and motors for continuously adjusting the turns ratio.

Another method is the use of high-frequency switching converters. The ac mains voltage is converted into a dc voltage by an ac-dc converter and the dc voltage is converted into an ac voltage by a dc-ac converter [2]. Thus, the overall system can flexibly provide a high-quality variable voltage and variable frequency output at v_L . However, as the input energy from the ac mains is processed twice, the overall efficiency is low. For example, if the efficiencies of the ac-dc and the dc-ac converters are 0.95, the overall efficiency is $0.95 * 0.95 = 0.90$.

Apart from using ac-dc-ac conversion approach, an ac-ac converter such as cycloconverter can be used to provide a controllable voltage at mains frequency. In [9], a power converter is used to chop the ac sinusoidal voltage into voltage pulses with the sinusoidal envelope. Similar approach is used in [10, 11]. However, considerable current harmonics will be generated in the process, leading to harmonic pollution problems in the power system. It is unsuitable for lamps, such as HID lamps, which are sensitive to the excitation voltage. It may cause undesirable acoustic resonance and flickering effect.

Another approach [12, 13] is the use of an external current-control power circuit to control the magnitude of the input current at mains frequency. Instead of transforming the voltage magnitude, this method adjusts the input current taken from the ac mains. As the active power taken from the ac mains is proportional to the product of the ac mains voltage and current, this can thus control the overall power delivered to the lamps.

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Method II - Control of the ballast-lamp impedance path

Instead of transforming the ac mains voltage directly, Fig. 4(c) illustrates another dimming method that the

apparatus is connected in series with the lamp system. The connected apparatus is a variable reactance that it does not dissipate any active power ideally. As the overall impedance of the lamp system is adjustable, the magnitude of v_L and
5 input current becomes adjustable.

As discussed in [14], a two-step inductor consisting of two series inductors is used for the choke in the ballast. With a switch that can bypass one of the two inductors, the overall inductance can be altered in a discrete manner.

10 In [15], a saturable reactor is used in the ballast that can dim the lamps continuously within a limited range. By adding an extra winding to the reactor and injecting a dc current into this extra winding, the reactor core can be saturated, so that the impedance of the inductor in the
15 ballast can be changed. The resulting effect is to adjust the current flowing to the lamps. A variant in [16] uses a variable reactance with the current to the control winding being provided by a multi-tapped autotransformer, so that different combinations of equivalent series impedance can be
20 realized.

Instead of using passive elements, another approach [17, 18] is based on creating a voltage source connecting in series with the lamp path. In [17], a dc/ac converter is connected in series with the lamp system. The dc side of the
25 converter is connected to another ac/dc converter, which is supplied from the ac mains. Both converters have to handle active and reactive power. In other words, there is a circulating energy between the two converters. Similar idea is used in [18] that the implementation is based on using
30 transformer coupling. Nevertheless, this circulating energy will introduce energy loss in the system. Apart from

lowering the efficiency, it is also necessary to handle the thermal issue.

Method III - Control of the lamp terminal impedance

5 As illustrated in Fig. 4(d), the third approach is to use an apparatus that can divert the current from the ballast. The overall effect is to reduce the lamp current i_{Lamp} . In [19], a switchable capacitor is connected across a lamp. If dimming is required, the capacitor is switched on,
10 so that part of the current from the ballast will be diverted away from the lamp into the capacitor. In this way, the lamp current and hence the lamp power can be controlled in a discrete manner.

 Comparing the above methods, Methods I and II are
15 suitable for dimming a plurality of lamps, particularly for existing installation. Method III requires modification or installation of the dimming apparatus on each individual lamp. Although all of the above methods can dim the lamps with magnetic ballasts, they have their respective
20 limitations of

- 1) requiring expensive and bulky mechanical construction [7,8],
- 2) introducing undesirable harmonic pollution to the power system [9]-[13],
- 25 3) inapplicable for dimming a plurality of lamps [14, 15, 19],
- 4) handling the total active and reactive power of the load [7]-[13],
- 5) providing discrete dimming only [7, 8], [14]-[16], [19]
- 30 6) being practically difficult for central or automatic control [7, 8, 14, 15, 17],

- 7) reducing the input power factor of the entire lighting system when the lamps are dimmed [14, 15, 16], and
- 8) handling dissipative circulating energy [17, 18].

5

SUMMARY OF INVENTION

According to the present invention there is provided apparatus for providing improved power quality and dimming control for an electrical lamp or generally electrical lighting systems including systems formed by a plurality of individual lamps. The apparatus achieves the dimming function with real energy saving by controlling the voltage available to the lighting system without handling the active power of the system. Instead, it only handles the reactive power of the entire system. The power rating of the dimmer will be much smaller than the full power rating of the lighting system. The structure of a preferred embodiment is shown in Fig. 5(a). Installation of the apparatus is similar to Method II in Fig 4(c) that the apparatus is connected in series with the lighting system. Instead of a reactance, the apparatus is a reactive power controller (RPC), which will insert an auxiliary voltage between the ac mains voltage v_{ac} and the ballast input v_L . Fig. 5(a) shows the connection of a RPC, RPC_1, connecting between the ac mains and lighting system. The auxiliary voltage is maintained at 90 or 270 degrees out of phase with the current i_L flowing through said apparatus, and wherein the magnitude of the auxiliary voltage is used for varying the voltage applied the lamp.

In one preferred embodiment the RPC in the apparatus is a dc-ac converter, consisting of a half-bridge converter circuit in Fig. 6(a) or a full-bridge converter circuit in Fig. 6(b). The dc side of either configuration is connected to a dc source. This dc source can be an externally

controlled dc voltage source or a capacitor. The ac side of the bridge circuit is connected to the nodes 'A' and 'B' in Fig. 5(a) through an inductor L .

The magnitude of the voltage, and hence the current, supplying to the lamp are varied by controlling the amount of reactive power generated from or absorbed by the reactive power controller RPC_1 in Fig. 5(a). However, with the use of RPC_1 to adjust the active power delivery to the lamps, the input power factor of the entire system in Fig. 5(a) will be reduced. As illustrated in Fig. 5(b), a second reactive power controller RPC_2 is therefore connected across the ac mains. Its function acts as a power factor improvement circuit. RPC_2 absorbs reactive power from or generates reactive power to the entire lighting system with the RPC_1 in Fig. 5(a), so that the overall power factor of the system can be improved. Ideally, the overall reactive power absorbed or generated from the whole is zero, so that the input power factor of the whole system is maintained at unity. Because the two reactive power controllers RPC_1 and RPC_2 essentially handle reactive power only, theoretically no active power is involved in the circuit operation (except that there will be, in practice, some conduction and switching losses in the power electronic devices, and copper and magnetic core losses in the inductors). Therefore, this proposed dimming method based on reactive power control has the ability of achieving high energy efficiency. It is important to note that the proposed RPC configuration operates in a different manner from conventional two-stage ac-dc converter and dc-ac inverter configuration [17]. While the former configuration handles reactive power only, the latter configuration handles both real and reactive power. There is no circulating energy between the two converters.

The value of the dc link capacitor (i.e. the two capacitors (Fig. 6a) or single capacitor (Fig. 6b) that is used as a voltage source) can be made smaller than the one required in [17], because the amount of energy handled by the two
5 converters is less than that in [17]. Therefore, the proposed configuration has a much small Volt-Ampere rating and higher energy efficiency than those of conventional two-stage ac-dc-ac power converter systems.

Put another way, an advantage of the present invention
10 over prior art devices such as those described in [17] and [18] is that in the present invention, the RPC develops a voltage that is substantially 90° or 270° out of phase with the current flowing through the RPC. Thus the RPC appears, to a lamp ballast or to the AC mains supply, to be either a
15 substantially "pure" inductance or a substantially "pure" capacitance. By "pure", it is meant that the effective resistance of the RPC is negligible compared to its reactance impedance so that the RPC can be regarded as a pure capacitor or a pure inductor, without significant
20 series resistance. As those skilled in the art will appreciate, capacitors and inductors do not dissipate energy (except that is, for secondary effects such as dielectric losses in capacitors or hysteresis losses in inductors).

In contrast, prior art devices such as those described
25 in [17] and [18] have a complex impedance that includes both a reactive impedance together with a significant real impedance. As those skilled in the art will appreciate, a real impedance is equivalent to a resistor. Thus significant electrical power will be dissipated across the resistive
30 real impedance.

As the two RPCs are dc/ac power converters, the circuit complexity and control method can be simplified in an

advantageous embodiment by connecting the dc sides of RPC_1 and RPC_2 together. However, there may seem to be some grounding problems for the two RPCs. The two RPCs may not be directly together and may require isolation transformers to isolate the RPC from either the series or parallel branch. In this patent, a half-bridge-derived converter circuit configuration will be discussed. Without using isolation transformer, the series and parallel RPCs can be developed with the same dc link (Fig.11) in this proposal.

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BRIEF DESCRIPTION OF THE DRAWINGS

Figs. 1(a)-(b) illustrate the operation of a prior art triac-based dimmer,

Fig. 2(a)-(c) shows the general structure of electronic ballast for discharge lamps,

Fig. 3 illustrates the infrastructure of the lighting system using a dimmable electronic ballast for individual lamp, Fig. 4(a)-(d) depict various prior art dimming methods for lamps with magnetic ballasts,

Fig. 5(a)-(b) show various configurations of the dimming apparatus,

Fig. 6(a)-(c) illustrate the schematics of the reactive power controller,

Fig. 7(a)-(b) shows the phasor diagram and the power triangle of the system when the lighting system is inductive, Fig. 8(a)-(b) shows the phasor diagram and the power triangle of the system when the lighting system is capacitive,

Fig. 9 illustrates the structure of the RPC for improving the input power factor,

Figs. 10 (a)-(g) shows the possible implementation of the dimming control apparatus with high power factor,

Fig. 11 show the preferred embodiment that RPC_1 and RPC_2 share the same dc source,

Fig. 12(a)-(d) shows the equivalent circuit of the entire system at different combinations of v_{inv} and $v_{P_{inv}}$, and

5 Fig. 13 shows an embodiment which uses AC/AC converters.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

A. *Equivalent circuit of the RPC*

10 An equivalent circuit showing the operation of the RPC is illustrated in Fig. 6(c), in which the half-bridge [(Fig. 6(a)] or the full-bridge [Fig. 6(b)] converter is modeled by a sinusoidal voltage source v_{inv} with the same frequency as the ac mains. The dc side of the converter is connected to
 15 an externally controlled dc voltage source or a capacitor. The nodes 'A' and 'B' are connected to a fictitious ac source v_a through an inductor L . The fundamental frequency of v_a is the same as the line frequency. The switches in the two bridge circuits, [S_1 and S_2 in Fig. 6(a)] and [S_1 to S_4
 20 in Fig. 6(b)], are switched at a frequency much higher than the frequency of the ac mains. The gate signals driving the switches are modulated with the frequency of the ac mains. Many pulse width modulation (PWM) schemes for driving the switches can be used. Examples include sinusoidal PWM, PWM
 25 scheme with selective harmonic elimination, uniform sampled PWM, etc [2]. The frequency spectrum of the converter output across 'C' and 'D' in Fig. 6 consist of mainly the line frequency, the switching frequency, and the inner and cross-modulation of the two frequencies. As the inductor L
 30 is used to filter out the undesirable high-frequency components appearing across the nodes 'A' and 'B', active and reactive energy flow between v_a and RPC can be

represented by considering the line frequency only. Hence, using v_{inv} in Fig. 6(c) to model the converter is applicable.

B. Operating Principles of the RPC

5 The line-frequency model shown in Fig. 6(c) is used to explain the operating principles of the RPC. The power P and the reactive power Q flow through RPC can be expressed as [3]

$$P = \frac{v_a v_{inv}}{2\pi f L} \sin \delta \quad (1)$$

$$Q = \frac{v_a (v_a - v_{inv} \cos \delta)}{2\pi f L} \quad (2)$$

10 where f is the mains frequency and δ is the phase difference between v_a and v_{inv} .

Based on Eq. (1), the RPC has three possible operating modes:

Mode I - If $\delta > 0$, $P > 0$, the inverter absorbs energy, and
15 the capacitor voltage v_c increases.

Mode II - If $\delta < 0$, $P < 0$, the inverter releases energy and v_c decreases.

Mode III - If $\delta = 0$, $P = 0$ and v_c remains unchanged. Q is determined by the magnitudes of v_{inv} and v_a . If $v_a > v_{inv}$,
20 $Q > 0$. The RPC acts as a reactive power absorber. Conversely, if $v_a < v_{inv}$, $Q < 0$. The RPC acts as a reactive power generator.

Ideally, the RPC is operated in Mode III and acts as either a reactive power absorber or a reactive power
25 generator. In practice, δ is slightly larger than zero, because the absorbed energy is used to compensate the practical energy loss in the RPC. As depicted in Fig. 6(b), the value of v_{inv} determines the values of Q , v_a , and hence the power delivered to the lamps. Depending on the type of

the dc source in the RPC, different control methodologies can be applied.

1. *Externally controlled voltage source*

5 If the dc source is an externally controlled dc voltage source, the amount of Q can be controlled by adjusting the modulation index M of the bridge circuit and/or the magnitude of the dc source voltage v_{dc} . As the high-frequency ripples will be attenuated by the inductor, only
10 the fundamental component (i.e., the line frequency) will be considered. As shown in [2],

$$v_{inv} = \frac{1}{\sqrt{2}} M v_{dc} \quad (3)$$

where v_{inv} is the rms value.

Thus, both M and v_{dc} can be used to vary v_{inv} .

15

2. *Dc capacitor*

If the dc side is a capacitor, control of v_{inv} is based on varying M and/or δ . Changing the value of M is similar to eq. (3) that

20

$$v_{inv} = \frac{1}{\sqrt{2}} M v_c \quad (4)$$

Another way of varying the capacitor voltage v_c , and hence v_{inv} , is to make RPC_1 enter into either Mode I or Mode II by adjusting δ . Afterwards, RPC_1 reverts back to Mode III. The ultimate function is to regulate v_c at a desired level so
25 that there will be no net flow of power in the RPC. This function can be realized by using a phase-lock loop to synchronize v_{inv} with v_a and an error amplifier to adjust the value of δ and/or M .

30 C. *Dimming of the lamps*

Dimming of the lamps is achieved by controlling the voltage across the lamp system. Fig. 7(a)-(b) show the phasor diagram and the power diagram of the system, when the lamp system is inductive. Fig. 8(a)-(b) show the respective
 5 diagrams of the system, when the lamp system is capacitive.

1. Inductive lamp system

Fig. 7 depicts the dimming operation at two power levels. When the input power of the lamp system is P_1 , the
 10 supply voltage to the lamp system is v_{L_1} and the supply current is i_{L_1} . i_{L_1} lags v_{L_1} by a phase difference of ϕ_1 . As the RPC is connected in series with the lamp system, the current flowing through it is also equal to i_{L_1} . As shown in Fig. 5(a), the required voltage vector of the RPC v_{a_1} is
 15 perpendicular to i_{L_1} , so that the RPC will not get any real power from the ac mains. i_{L_1} lags v_{a_1} . It means that the RPC absorbs reactive power. As shown in Fig. 7(b), the reactive power consists of two components, including the reactive power absorbed by the lamp system Q_1 and the
 20 reactive power absorbed by the RPC Q_{a_1} .

If the lamp system is dimmed down to a power level of P_2 , the supply voltage becomes v_{L_2} and the supply current is i_{L_2} . i_{L_2} lags v_{L_2} by a phase difference of ϕ_2 . The magnitude of v_{L_2} is smaller than the magnitude of v_{L_1} . The vector of
 25 the RPC voltage should be perpendicular to i_{L_2} and its magnitude should be higher than that of v_{a_1} . Therefore, in order to achieve the dimming function, the magnitude of the dc-side voltage must be increased. In general, the reactive power absorbed by the lamp system decreases (i.e., $Q_2 < Q_1$).
 30 The reactive power absorbed by RPC is changed from Q_{a_1} to Q_{a_2} .

2. Capacitive lamp system

Fig. 8 depicts the dimming operation at two power levels. When the input power of the lamp system is P_1 , the supply voltage to the lamp system is v_{L_1} and the supply current is i_{L_1} . i_{L_1} leads v_{L_1} by a phase difference of ϕ_1 . As shown in Fig. 8(a), the required voltage vector of the RPC v_{a_1} is still perpendicular to i_{L_1} . i_{L_1} leads v_{a_1} . It means that the RPC generates reactive power. As shown in Fig. 8(b), the reactive power consists of two components, including the reactive power generated by the lamp system Q_1 and the reactive power generated by the RPC Q_{a_1} .

If the lamp system is dimmed down to a power level of P_2 , the supply voltage becomes v_{L_2} and the supply current is i_{L_2} . i_{L_2} leads v_{L_2} by a phase difference of ϕ_2 . The magnitude of v_{L_2} is smaller than the magnitude of v_{L_1} . The vector of the RPC voltage should also be perpendicular to i_{L_2} and its magnitude should be higher than that of v_{a_1} . Therefore, in order to achieve the dimming function, the magnitude of the dc-side voltage must be increased. In general, the reactive power generated by the lamp system decreases (i.e., $Q_2 < Q_1$). The reactive power absorbed by RPC is changed from Q_{a_1} to Q_{a_2} .

D. High Power Factor Configuration

As depicted in Fig. 7 and Fig. 8, in addition to the reactive power absorbed or generated by the lamp system, the RPC will absorb or generate additional reactive power from the ac mains. This operation will cause a reduction of the input power factor of the whole lighting system. The power factor is reduced from $\cos \theta_1$ to $\cos \theta_2$, when the lamp power is adjusted from P_1 to P_2 . Although connecting a capacitor across the ac mains input can improve the power factor, the

required capacitor value is lamp-power-dependent. The power factor can be kept unity at any lamp power by connecting another controller RPC_2 across the ac mains as in Fig. 5(b).

For inductive lamp systems, the required reactive power Q_P [Fig. 7(b)] that needs to be generated by RPC_2 is equal to the sum of the reactive power absorbed by the lamp system and RPC_1 at any power level. If the input power of the lamp system is P_1 ,

$$Q_{P_1} = Q_{a_1} + Q_1 \quad (5)$$

If the input power of the lamp system is P_2 ,

$$Q_{P_2} = Q_{a_2} + Q_2 \quad (6)$$

Fig. 7(b) illustrates the vectors of Q_{P_1} and Q_{P_2} . Thus, Q_P is load-dependent.

For capacitive lamp systems, the required reactive power Q_P [Fig. 8(b)] that needs to be absorbed by RPC_2 is equal to the sum of the reactive power generated by the lamp system and RPC_1 at any power level. Eqs. (5) and (6) are still valid. Fig. 8(b) illustrates the vectors of Q_{P_1} and Q_{P_2} . Again, Q_P is load-dependent.

In both inductive and capacitive lamp systems, Q_P is determined by eq. (2). As illustrated in Fig. 9, the bridge converter voltage v_{P_inv} determines the magnitude of Q_P . Eqs. (1) and (2) show the power and reactive flow between the ac mains and RPC_2. That is,

$$P_P = \frac{v_{ac} v_{P_inv}}{2\pi f L_P} \sin \delta_P \quad (7)$$

$$Q_P = \frac{v_{ac} (v_{ac} - v_{P_inv} \cos \delta_P)}{2\pi f L_P} \quad (8)$$

where δ_P is the phase difference between v_{ac} and v_{P_inv} .

Again, RPC_2 has three possible operating modes:

Mode I - If $\delta_P > 0$, $P_P > 0$, the inverter absorbs energy, and the capacitor voltage v_{P_C} increases.

Mode II - If $\delta_P < 0$, $P_P < 0$, the inverter releases energy and v_{P_C} decreases.

5 Mode III - If $\delta_P = 0$, $P_P = 0$ and v_{P_C} remains unchanged. Q_P is determined by the magnitudes of v_{P_inv} and v_{ac} . If $v_{ac} > v_{P_inv}$, $Q_P > 0$. The RPC_2 acts as a reactive power absorber. Conversely, if $v_{ac} < v_{P_inv}$, $Q_P < 0$. RPC_2 acts as a reactive power generator.

10 Control of Q_P is based on monitoring the phase shift between the ac mains voltage and that of the overall input current. Similar to RPC_1, the voltage v_{P_inv} determines Q_P and is controlled by adjusting the modulation index of the bridge in RPC_2 and/or δ_P . For example, if the lamp system
15 is inductive, RPC_1 will be operating as a reactive power absorber and RPC_2 will be operating as a reactive power generator. If the input current lags the supply voltage, the control circuit will increase the dc link voltage (i.e. the voltage of the capacitor, or capacitors, that are used
20 as DC voltage source) of RPC_2, so that RPC_2 will generate more reactive power and hence the phase difference between the supply voltage and input current will be reduced. If the input current leads the supply voltage, the control circuit will decrease the dc link voltage of RPC_2, so that RPC_2
25 will generate less reactive power and hence the phase difference between the supply voltage and input current will be reduced. As shown in Fig. 7 and Fig. 8, the overall input currents $i_{L_1'}$ and $i_{L_2'}$ for power levels P_1 and P_2 , respectively, will be in phase with the ac mains and thus
30 the power factor is unity.

E. Sharing the same dc source for RPC_1 and RPC_2

Fig. 10 shows possible implementation of the dimming control apparatus with high power factor. Fig. 10(a) shows one possibility that two half-bridge converters can be used for RPC_1 and RPC_2. In this method, four dc capacitors and four semiconductor switches are required. Fig. 10(b) shows another possible method that two full-bridge converters can be used for RPC_1 and RPC_2. In this case, two capacitors and eight switches are required. Other possibilities are the combinations of using half-bridge and full-bridge converters for RPC_1 and RPC_2. Fig. 10(c) shows the possibility that RPC_1 uses a half-bridge converter and RPC_2 uses a full-bridge converter. Fig. 10(d) shows the possibility that RPC_1 uses a full-bridge converter and RPC_2 uses a half-bridge converter.

If the dc link sources of RPC_1 and RPC_2 are combined, the number of capacitors can be reduced. However, if the two controllers shown in Fig. 8 are connected directly, a short circuit path between the live and neutral may be formed. In order to avoid the short circuit problem, RPC_1 and RPC_2 can be isolated by using transformers. Figs. 10(e)-(g) show different combinations of using transformers to isolate the RPC_1 and/or RPC_2. This will introduce additional power loss on the transformers.

Fig. 11 shows an embodiment that RPC_1 and RPC_2 share the same dc source and no transformers are needed. As encircled in Fig. 11, RPC_1 is formed by S_1 , S_2 and the two capacitors, while RPC_2 is formed by S_3 , S_4 and the two capacitors. Its operation can be explained by studying the overall operations of RPC_1 and RPC_2 in the dimming apparatus. Fig. 12(a)-(d) shows the equivalent circuit of the entire system at different combinations of v_{inv} and v_{p_inv} . As v_{inv} and v_{p_inv} can be positive or negative, four possible

combinations are resulted. S_1 , S_2 , L , and the two capacitors formed the RPC_1, while S_3 , S_4 , L_p , and the two capacitors formed the RPC_2. When S_1 and S_3 are switched on, the circuit shown in Fig. 12(a) is formed. When S_2 and S_3 are
5 switched on, the circuit shown in Fig. 12(b) is formed. When S_1 and S_4 are switched on, the circuit shown in Fig. 12(c) is formed. Finally, when S_2 and S_4 are switched on, the circuit shown in Fig. 12(d) is formed.

On the one hand, as explained above, v_L can be varied
10 by controlling the modulating index of the converter formed by S_1 and S_2 and the phase shift between v_{inv} and v_a . On the other hand, the power factor can be improved by controlling the phase shift between v_{ac} and v_{P_inv} , and the modulation index of the RPC_2. The two converters do not handle any
15 active power in the whole system.

Adjusting the phase shift between v_{ac} and v_{P_inv} , and the modulation index of the inverter, formed by the switches S_3 and S_4 , can control the amount of reactive power generated or absorbed by RPC_2. As the dc source is common to RPC_1
20 and RPC_2, dimming of the lamps can be performed by varying the modulation index of the inverter formed by the switches S_1 and S_2 .

In alternative embodiments, an AC voltage source (instead of a DC voltage source) and an AC/AC voltage
25 converter (instead of a DC/AC voltage converter) may be used to develop the auxiliary AC voltage across RPC_1 and/or RPC_2, as shown at Fig. 13.

The frequency of an AC main supply will typically vary. For example a nominally 50Hz AC mains supply may vary
30 between 49Hz and 51Hz. Thus in many embodiments it will be desirable to include a frequency locking means such as a frequency locked loop, or a phase locked loop (PLL).

Ideally, the voltage and current flowing through RPC_1 and/or RPC_2 will be exactly 90° out of phase so that RPC_1 and/or RPC_2 behave as perfect inductors or perfect capacitors. In practice, there will be some losses in RPC_1 and/or RPC_2. Some losses will result from switching losses, e.g. from the half-bridge or full-bridge circuitry. Also, control circuitry will require electrical power to function and this electrical power will appear, to the magnetic ballast and to the AC mains supply, as a small real resistance. Thus although it is preferred that the voltage and current are exactly 90° out of phase as for a pure reactance, the invention may be put into effect when the voltage and current are within 1°, 5° or 10° of being 90° out of phase.

As well as the full-bridge and half-bridge topologies described above, other types of power converter may be used to generate the auxiliary voltage. It is anticipated that in most embodiments, power semiconductor devices will be used as the switches for, say, the half-bridge or the full-bridge. An example of an appropriate power semiconductor device is an insulated gate bipolar transistor (IGBT) although, as those skilled in the art will appreciate, other types of devices may be used instead.

The present invention may be applied to electronic lamp ballasts as well as to magnetic lamp ballasts. As those skilled in the art will appreciate, some electronic ballasts include power regulation, for example to allow operation of lamps from an AC mains supply in the range 110V to 240V. The present invention may not be so effective when used in conjunction with electronic ballasts that include power regulation as, if the RPC increases the effective impedance of the AC mains supply, such electronic ballasts will reduce

their equivalent impedance which will to some extent counteract the impedance increase of the RPC.

The present invention may be used with gaseous discharge lamps such as high pressure sodium lamps, low
5 pressure sodium lamps, fluorescent lamps and high intensity discharge lamps such as metal halide lamps.

The present invention relates in particular to a simple general purpose and non-intrusive dimming system that can be retro-fitted to existing lamps and which is non-intrusive in
10 the sense that when not in use the dimming system has no effect on the normal operation of the lamp. As shown in Fig. 9, a by-pass switch may be connected across RPC_1 and is open if RPC_1 is in operation. If RPC_1 is not in use, the by-pass switch will be closed and the lighting system will
15 be supplied from the ac mains with any interruption.

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10

CLAIMS:

1. A reactive power controller for dimming an AC mains lighting system, the reactive power controller
5 comprising:

first and second terminals for connection in series to an AC mains lighting system;

voltage developing means for developing an AC voltage at mains frequency between the first and second
10 terminals;

signal receiving means for receiving a dimming level control signal; and

control means for controlling the voltage developed by the voltage developing means on the basis of the
15 dimming level control signal, wherein the control means is operable to cause the voltage developing means to develop an AC voltage that is either substantially 90° or substantially 270° out of phase with current flowing from the first terminal to the second terminal.

2. A reactive power controller according to claim 1,
20 wherein the control means is operable to cause the voltage developing means to develop an AC voltage that is in the range of 80° to 100° or in the range of 260° to 280° out of phase with current flowing from the first
25 terminal to the second terminal.

3. A reactive power controller according to claim 2,
30 wherein the phase is in the range of 85° to 95° or in the range of 265° to 275° .

4. A reactive power controller according to claim 2, wherein the phase is in the range of 89° to 91° or in the range of 269° to 271° .

5. A reactive power controller according to claim 1, wherein the control means comprises a frequency locking means.

6. A reactive power controller according to any one of claim 1 to 5, wherein the control means comprises a phase locked loop (PLL).

7. A reactive power controller according to any one of claim 1 to 6, comprising means for receiving a DC voltage from a DC voltage source, wherein the voltage developing means is operable to convert the DC voltage to the AC voltage.

8. A reactive power controller according to any one of claims 1 to 6, comprising a DC voltage source, wherein the voltage developing means is operable to convert a DC voltage from the DC voltage source to the AC voltage.

9. A reactive power controller according to claim 8, wherein the control means is operable to control the voltage of the DC voltage source on the basis of the dimming level control signal, and thereby control the voltage developed by the voltage developing means.

10. A reactive power controller according to claims 8, wherein the DC voltage source comprises a capacitor means.

11. A reactive power controller according to claim 8, wherein the DC voltage source comprises two series¹ connected capacitor means.

5 12. A reactive power controller according to claim 10 or 11, wherein the control means is operable to control on the basis of the dimming level control signal the phase of the AC voltage relative to current flowing from the first terminal to the second terminal, to thereby
10 store or release energy in the capacitor means, to thereby change the voltage of the capacitor means, and thereby control the voltage developed by the voltage developing means.

15 13. A reactive power controller according to any one of claims 7 to 12, wherein the voltage developing means comprises switching means to convert the DC voltage to the AC voltage by alternately connecting the DC voltage source to the first and second terminals with a forward
20 polarity and then a reverse polarity.

14. A reactive power controller according to claim 13, wherein the switching means comprises a half-bridge converter.

25 15. A reactive power controller according to claim 13, wherein the switching means comprises a full bridge converter.

30 16. A reactive power controller according to any one of claims 13 to 15, wherein the switching means comprises a power semiconductor switching device.

17. A reactive power controller according to claim 16, wherein the switching means comprises an insulated gate bipolar transistor (IGBT).

5

18. A reactive power controller according to any one of claims 13 to 17, wherein the voltage developing means comprises inductor means for attenuating high frequency current ripples resulting from the switching means.

10

19. A reactive controller according to any one of claims 13 to 18, wherein the control means is operable to control on the basis of the dimming level control signal a modulation index of the switching means, and thereby control the voltage developed by the voltage developing means.

15

20. A reactive power controller according to any preceding claim, wherein the signal receiving means is operable to receive a DC voltage as the dimming level control signal.

20

21. A series-shunt reactive power controller for dimming an AC mains lighting system, the series-shunt reactive power controller comprising:

25

a first reactive power controller according to any one of claims 1 to 20, for series connection to the AC mains lighting system to reactively control the power supplied to the AC mains lighting system;

30

a second reactive power controller according to any one of claims 1 to 20, for shunt connection across the first reactive power controller and the AC mains

lighting system to improve the power factor of the first reactive power controller and the AC mains lighting system,

wherein the first and second reactive power controllers are electrically connected to share a common DC voltage source.

22. A series-shunt reactive power controller according to claim 21, wherein the first and second reactive power controllers are directly connected to share a common DC voltage source.

23. A series-shunt reactive power controller according to claim 21, comprising a transformer means to connect the first and second reactive power controllers to share a common DC voltage source.

24. A dimmable AC mains lighting system comprising:
means for receiving an incoming AC mains supply;
one or more lamp ballasts; and
a first reactive power controller according to any one of claims 1 to 20, wherein the first reactive power controller is series connected via its first and second terminals between the incoming mains supply and the one or more magnetic lamp ballasts.

25. A dimmable AC mains lighting system according to claim 24, wherein the one or more lamp ballasts comprise one or more magnetic lamp ballasts.

26. A dimmable AC mains lighting system according to claim 24, wherein the one or more lamp ballasts comprise one or more electronic lamp ballasts.

5 27. A dimmable AC mains lighting system according to any one of claims 24 to 26, comprising a second reactive power controller according to any one of claims 1 to 20, wherein the second reactive power controller is shunt connected via its first and second terminals across the
10 incoming mains supply.

28. A dimmable AC mains lighting system according to claim 27, wherein the first reactive power controller and the second reactive power controller are
15 electrically connected to share a common DC voltage source.

29. A dimmable AC mains lighting system according to any one of claims 24 to 28, wherein the means for
20 receiving an incoming AC mains supply comprises switchgear.

30. A dimmable AC mains lighting system according to any one of claims 24 to 29, comprising one or more lamps
25 respectively connected to the one or more lamp ballasts.

31. A dimmable lighting system according to claim 30, wherein the one or more lamps comprise gaseous discharge lamps.

32. A dimmable lighting system according to any one of claims 24 to 31, comprising by-pass switch means across the first reactive power controller.

5 33. A reactive power controller as hereinbefore described and/or with reference to any one of Figures 5 to 12.

10 34. A dimmable AC mains lighting system as hereinbefore described and/or with reference to any one of Figures 5 to 12.