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A new model of three-phase dimmer for star-connected inductive loads

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ABSTRACT: This work consists of the design and simulation of a new model of AC-AC electronic converter or dimmer, in terms of power arrangement and control strategy, for the variable-power supply of a three-phase star-mounted inductive load. The power circuit uses two bidirectional electronic switches, one in series to supply the load, and the other in parallel to freewheel the load current. The two switches are complementary controlled. Each switch consists of two transistors and two power diodes. The "Pulse Width Modulation with fixed frequency and variable duty cycle" control strategy is adopted to chop the supply voltage and vary the power supplied to the load. Simulation in Matlab Simulink enables the new model dimmer to be implemented and its performance to be compared with that of the conventional six-thyristor dimmer. The simulation shows that the new dimmer design is efficient and outperforms the old model by a wide margin, ensuring : (i) better energy efficiency, (ii) increased load life and stability, with lower voltage and current Harmonic Distortion Rates, and (iii) reduced disturbance to the supply network. The development and implementation of the new model dimmer will enable more effective and efficient variable-power supply and regulation of star-mounted industrial three-phase loads such as furnaces and electric motors.

KEYWORDS: three-phase dimmer, simulation, harmonics, power factor, efficiency.

I. INTRODUCTION

Control and power electronics enable industries to (i) regulate actuator output quantities by varying the power supply, and (ii) control the form of electrical energy. Dimmers enable the electrical power supplied to an AC load to be varied from a sinusoidal voltage source, and its behavior to be controlled [1] (speed of an induction motor, thermal power of a heating resistor, etc.). These loads are the main electrical actuators used in industry, and are connected in star or delta configuration. Conventional thyristor dimmers are widely used for their variation, but have the disadvantage of : (a) disturbing the supply network with input current harmonics and low power factors (b) affecting the durability and stability of equipment supplied with output voltage and current harmonics [2]-[4].

The aim of this work is to improve the performance of dimmers for star-mounted inductive loads [5]. The methodology adopted is to design a new three-phase dimmer model for star loads, in terms of control and power assembly, and to compare its performance with that of conventional dimmers, through simulation in Matlab Simulink.

The control strategy consists of fixed-frequency, variable duty cycle chopping, or Pulse Width Modulation [6], of the supply voltage. The power circuit uses two bidirectional electronic switches, with transistors, for each load branch, one connected in series for the power supply and the other in parallel to freewheel the inductor currents [7], [8].

The expected result is a new model of three-phase dimmer, for star loads, with high performance in terms of efficiency, Total Harmonic Distortion (THD) and power factor.

II. MATERIALS AND METHODS

a. Classicdimmer

i. Single-phase circuit

Two head-to-tail thyristors are used as bidirectional switches. Current pulses from the gates close the switch, while current cancellation opens it. To vary the output voltage, the current is allowed to flow for only part of the half-period for each half-

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wave. We then wait for an Alpha angle of less than 180° before pulsing the thyristor gates to command them.Current cancellation after each half-period naturally reopens the thyristor switch.

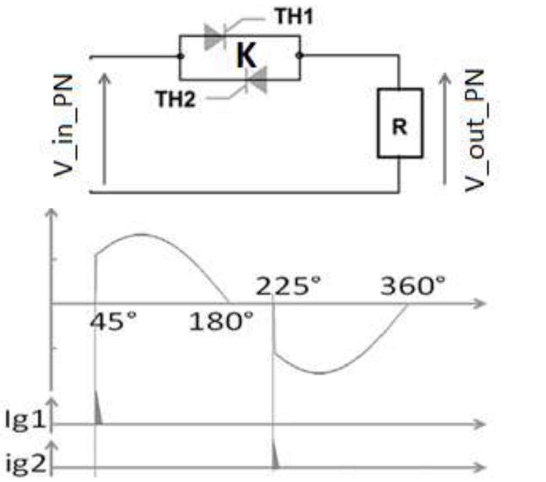

Fig. 1 Single-phase 2 thyristor dimmer power circuit, output voltage and gate pulse curves for alpha = 45°, R load

The alpha delay alters the sinusoidal shape of the supply voltage, causing voltage and current harmonics. It also increases the phase shift between mains voltage and load current, thus reducing the power factor value.

ii. Classic three-phase star load connection

If the power supply and the load are star-shaped, and have accessible neutral points, they can be connected to each other. The result is the equivalent of three single-phase dimmers.

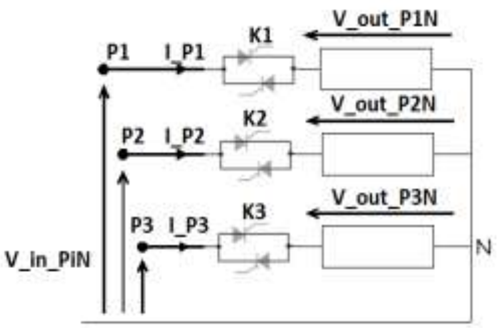

Fig. 2 Classic three-phase dimmer power circuit for star loads

b. New model dimmer

i. New-model single-phase dimmer

The new pulse-width-modulated dimmer chops the supply voltage and therefore only supplies the load with power at portions of each half-wave [1], [6], [9]-[11]. Two bidirectional switches, consisting of two transistors and two diodes, are used:

one in series with the load, to connect it to the source ;the other is connected in parallel to allow the current to pass in freewheeling mode.

Each switch consists of two transistors and two diodes.

These switches, controlled in complementary, are closed and opened at regular intervals, but with varying durations. This is the variable duty cycle pulse width modulation strategy. The control frequency must be carefully chosen: a too high value will ensure a quasi-sinusoidal output voltage, but will impact on the efficiency due to switching loss of the power transistors [12], [13].

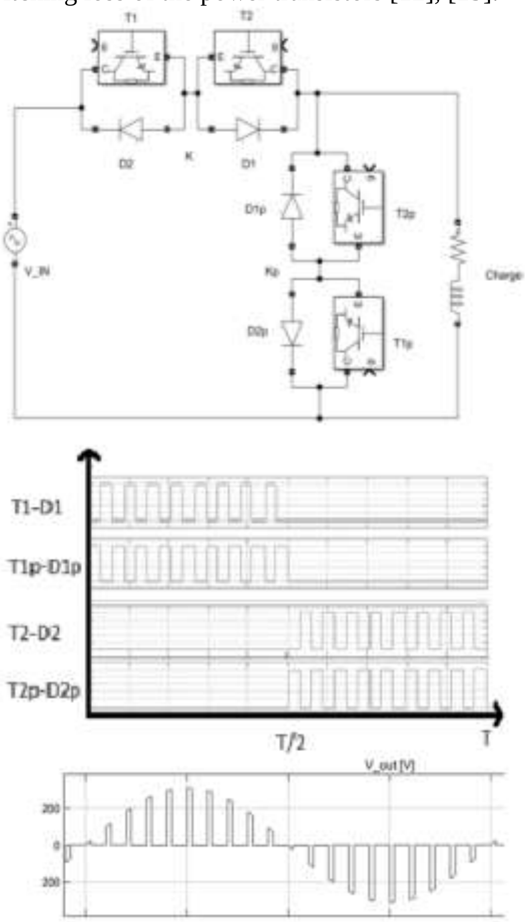

Fig. 3: Power circuit and control strategy for new single-phase dimmer model

During positive half-wave of the supply voltage, from [0; T/2], with T the period, T1-D1 and T1p-D1p conduct successively.

During negative half-wave of the supply voltage, from [T/2;T], T2-D2 and T2p-D2p conduct successively.

If T1-D1 or T2-D2 are conducting, the dimmer is said to be in the supply phase. If T1p-D1p or T2p-

D2p conduct, the dimmer is said to be in freewheel phase.
The pulse-width modulation control strategy, with fixed period and variable Alpha duty cycle, is adopted to supply the load only at portions of each half-wave.

ii. New-model three-phase dimmer for star loads

As with the classic dimmer, the new-style dimmer for three-phase star loads involves the use of three single-phase circuits, taking advantage of the load's accessible neutral point. The circuit therefore comprises six bidirectional switches(twelve transistors and twelve power diodes).

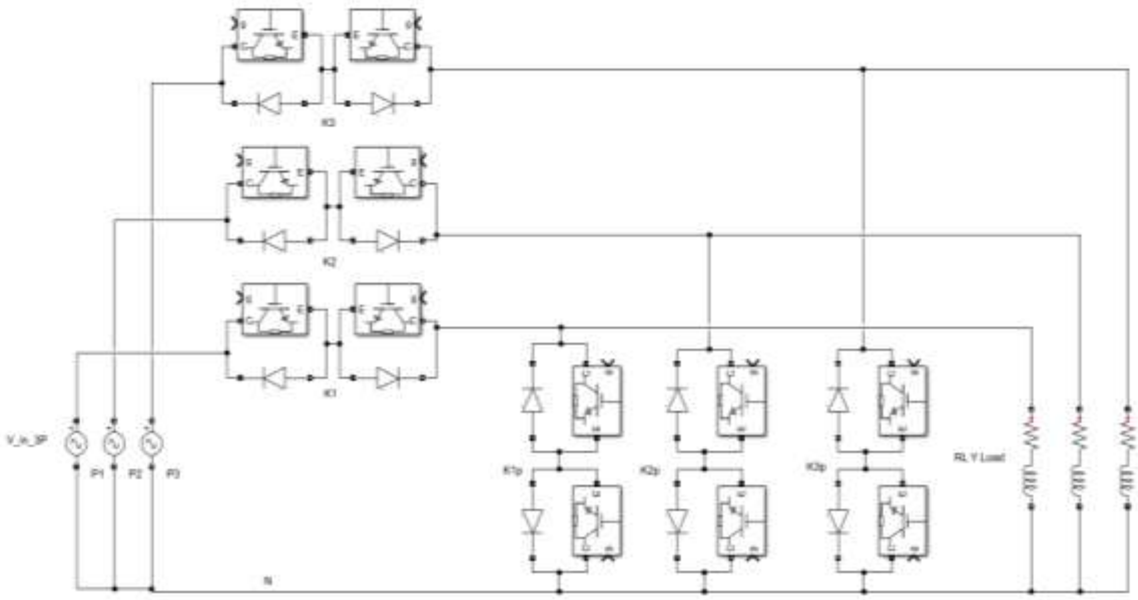

Fig. 4. power circuits of a new model dimmer for star load.

c. Simulation in Matlab Simulink

The Matlab Simulink software is used to simulate the operation of the converters in order to highlight their performance and make comparisons.

The dimmers will be powered by a three-phase sinusoidal voltage generator V_in = 220V RMS between phase and neutral, 380V between phases, 50Hz, and feeding a RL type load (cosfi power factor = 0.8 at 50Hz), mounted in star configuration.
Load: RL series R=17.6Ω R= 42.017mH
IGBTs will be used as transistors:
- Internal resistance 0.001 Ω
- Voltage drop during conduction 0.6V

For diodes
- Internal resistance 0.0001 Ω
- Voltage drop during conduction of 0.6V

Voltage, current and power measurements will be made to analyze the input and output behavior of each circuit. These measurements will be made for RMS values of the fundamental output voltage V_out equal to :
- 0.25xV_in RMS = 55V
- 0.5xV_in RMS = 110V
- 0.75xV_in RMS = 165V

d. Quantities to be measured

For three values of RMS output voltage, the quantities to be measured are :
- Input and output RMS voltage and current
- Input and output active and reactive power
- Active power efficiency
- Harmonic Distortion Rate or THD of output voltage, output current and input current.

III. RESULTS

a. Output signal patterns

The three output voltages between phase and neutral, and currents per phase, are read on an oscilloscope and displayed over 1.5 periods.

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Table 1. Dimmer output voltage and current curves

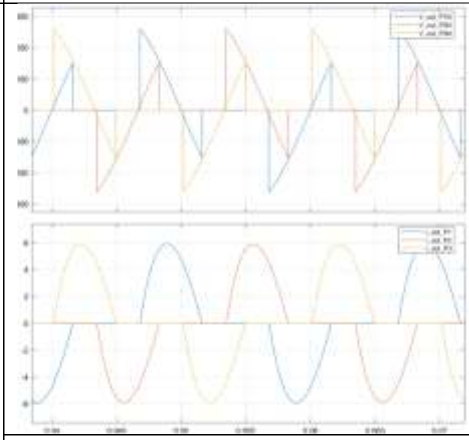
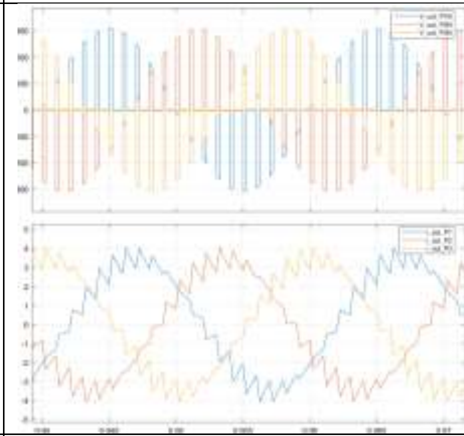
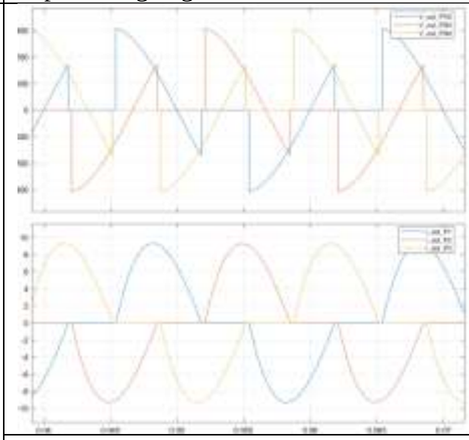
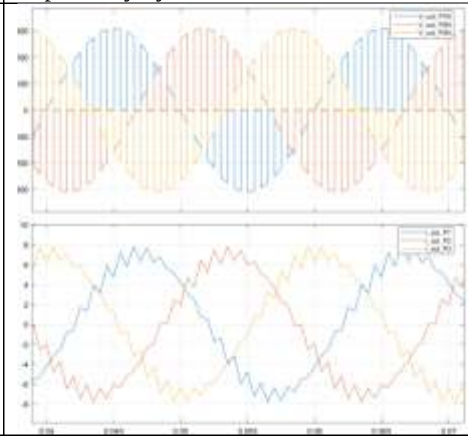
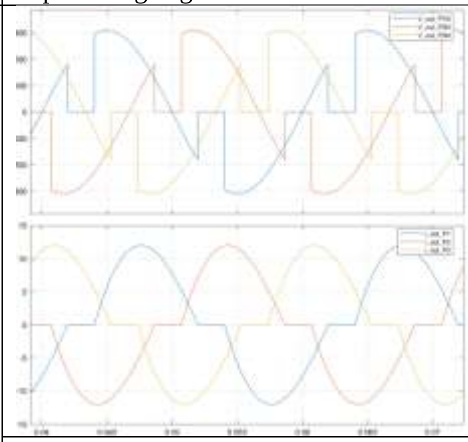
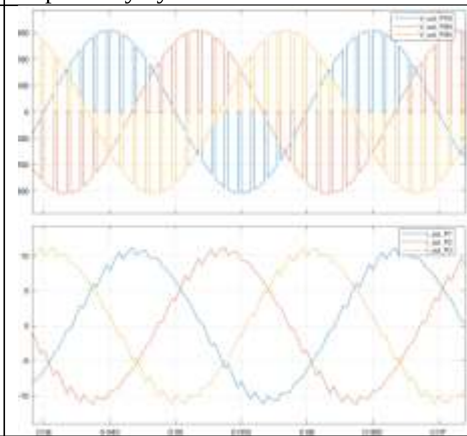
Ratio V_out RMS / V-in RMS	Three-phase dimmer for Y-mounted load models	
	Classical with thyristors	**New-model**
0.25	 Alpha firing angle = 6.8 ms	 Alpha duty cycle = 0.255
0.50	 Alpha firing angle = 5.425 ms	 Alpha duty cycle = 0.505
0.75	 Alpha firing angle = 4.03 ms	 Alpha duty cycle = 0.75

Fig. 5: Dimmer output voltage and current curves in Matlab Simulink

For the classic dimmer, the thyristors start to conduct after the control pulses, and open after the current is canceled. For the new model dimmer, the supply voltage is effectively chopped.

b. Variation of the RMS value of the fundamental output voltage

For conventional dimmers, the variation is obtained by acting on the value of the Alpha firing angle; for

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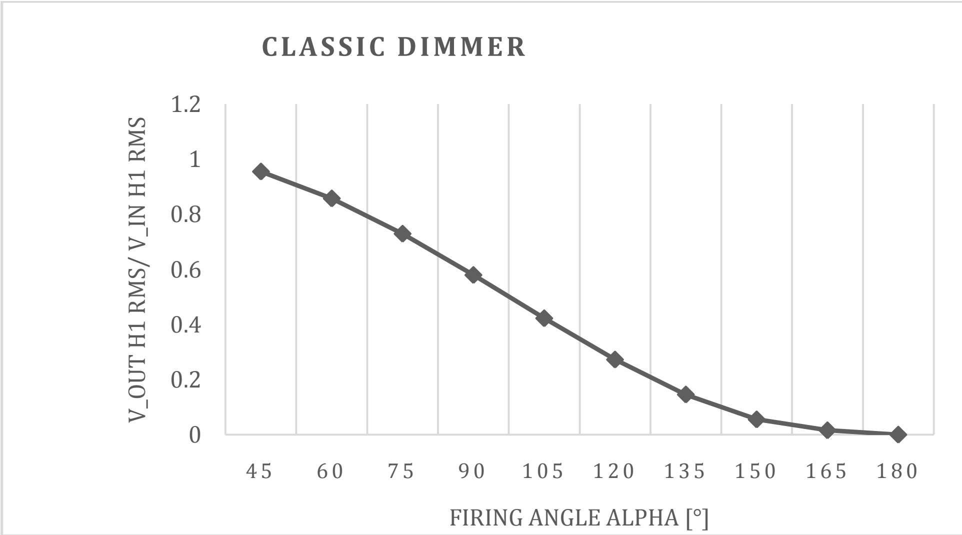
new-model dimmers, by acting on the value of the Alpha duty cycle.



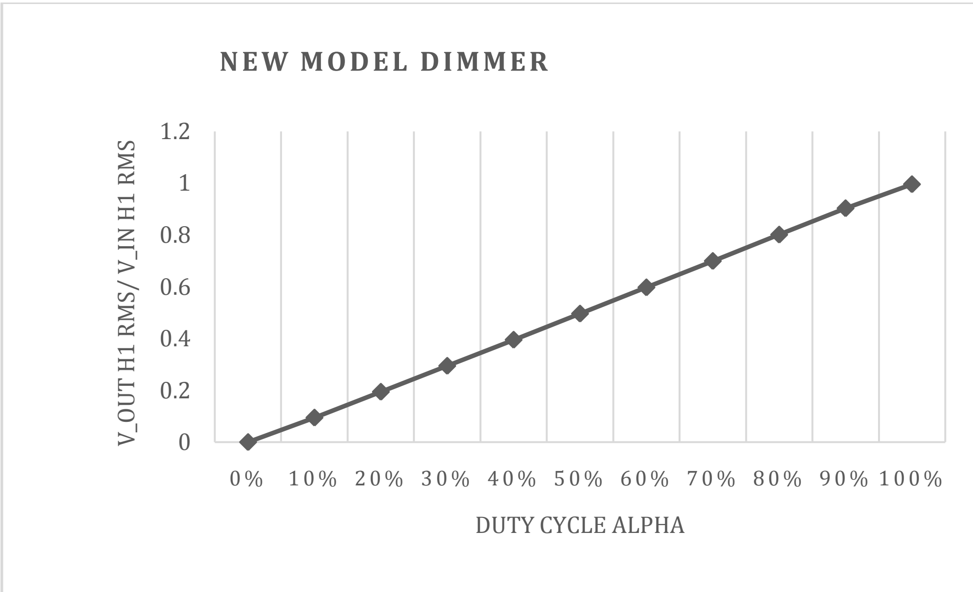


Fig. 6: Variation of fundamental output voltage

The output voltage varies linearly with Alpha for the new-model dimmer.

c. Harmonic Distortion Rate THD

i. THD of output voltage

For the three values of the fundamental output voltage between phase and neutral, the THD values are shown in Fig. 7.

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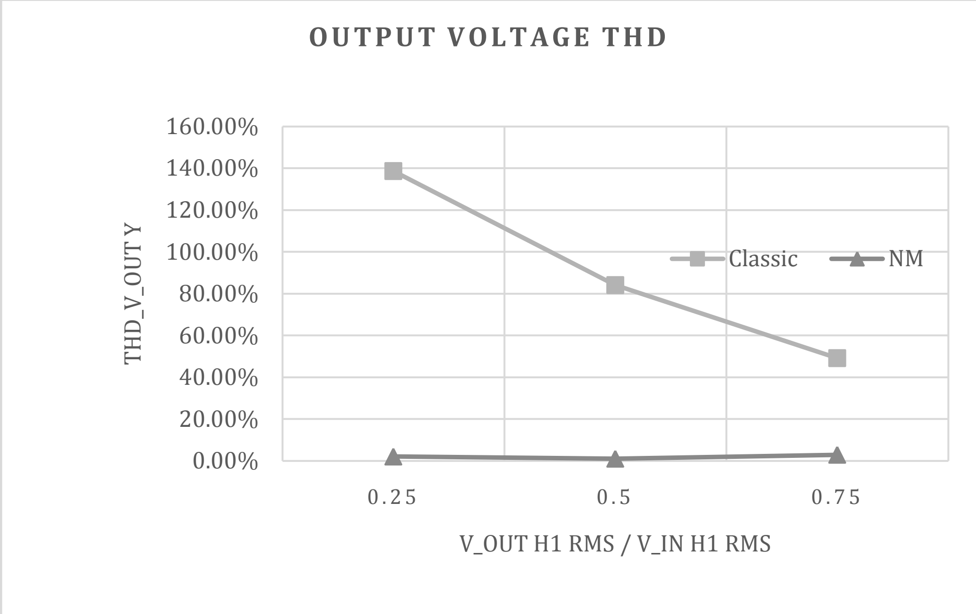
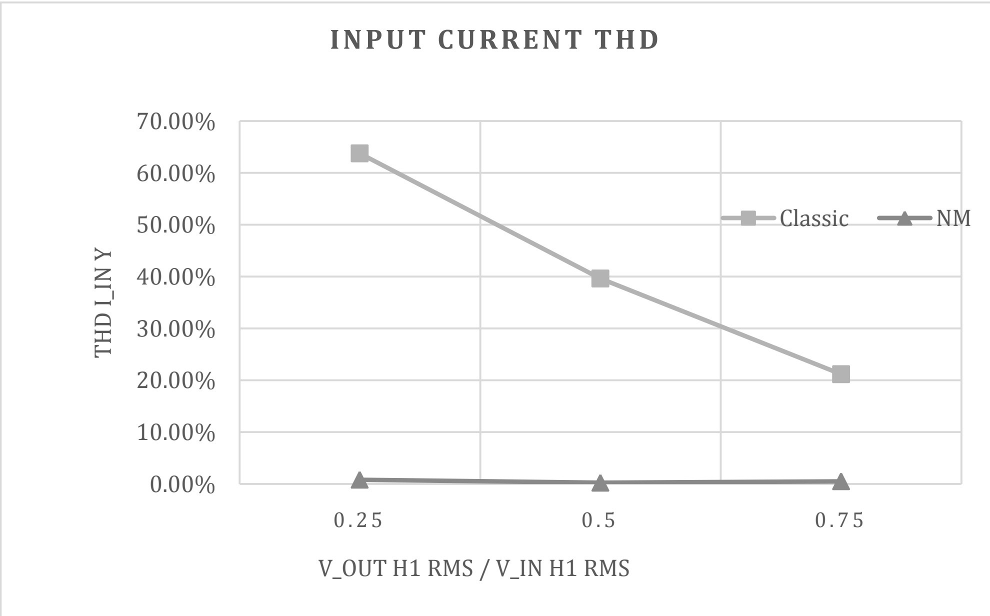


Fig. 7: THD of output voltage

The THD of the output phase-to-neutral voltage varies from 49.22% to 138.7% for the classic dimmer, and from 1.03% to 2.93% for the new model dimmer.

ii. THD of input and output current

For the three values of the fundamental output voltage between phase and neutral, the THD values are shown in Fig. 8.



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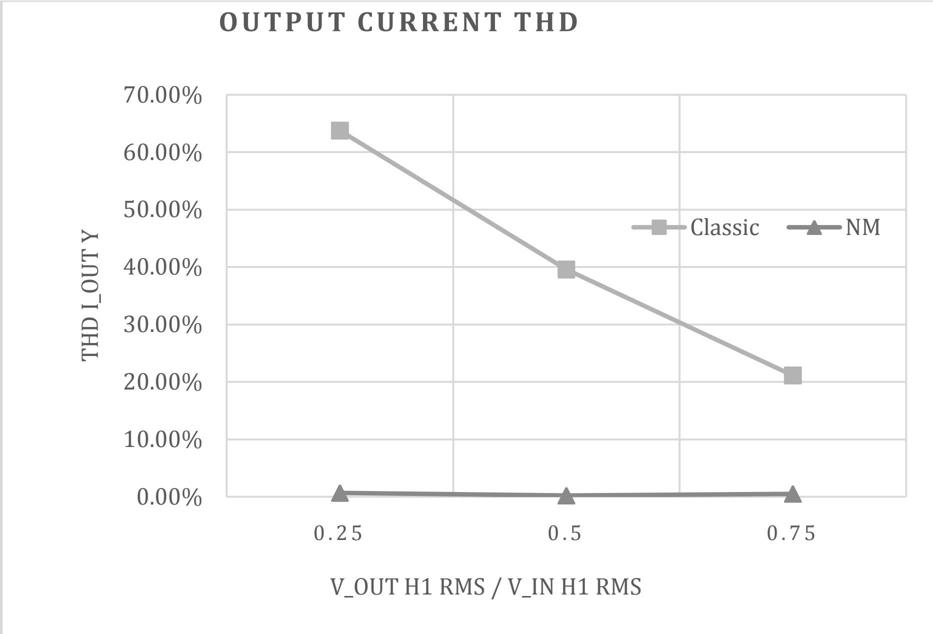


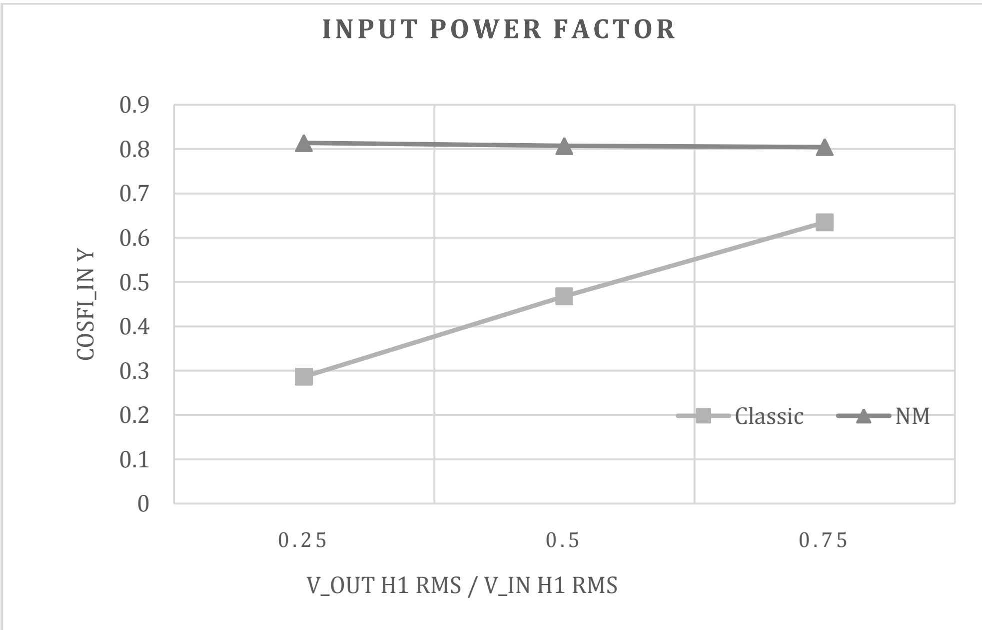
Fig. 8. input and output phase-current THD

The THD of the current per output phase varies from 21.16% to 63.77% for the classic dimmer and from 0.23% to 0.68% for the new model dimmer.

The THD of the current per input phase varies from 21.16% to 63.77% for the classic dimmer and from 0.24% to 0.83% for the new model dimmer.

d. Power factors

For the three values of the fundamental output voltage between phase and neutral, the values of the input and output power factors are shown in Fig. 9.



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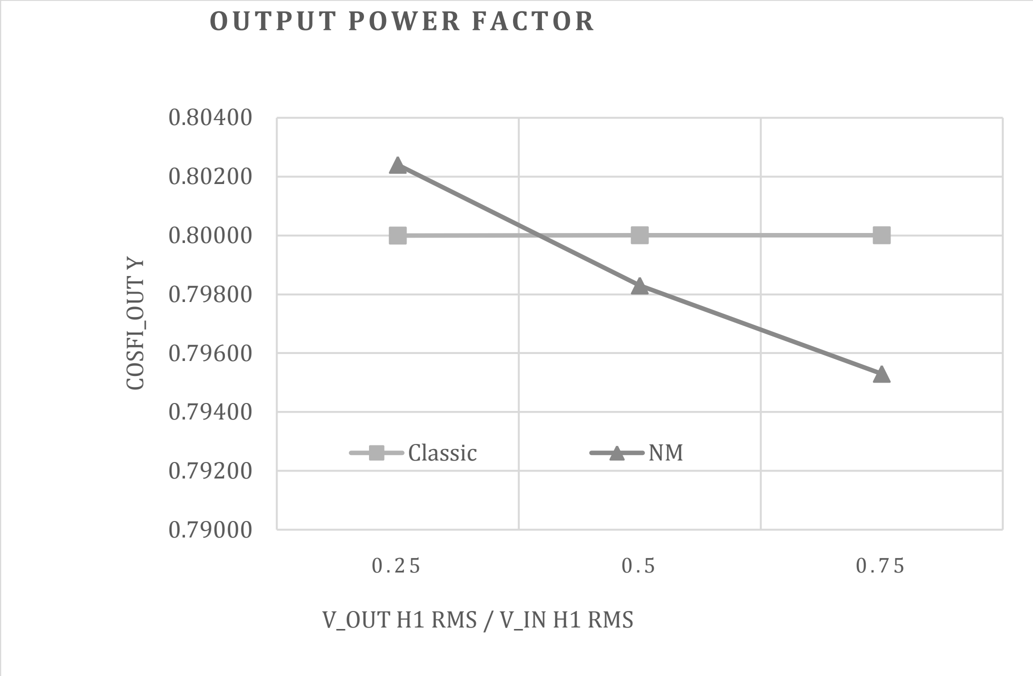

Fig. 9: Input and output power factors

The output power factor varies from 0.799 to 0.80 for the classic dimmer and from 0.795 to 0.80 for the new model dimmer.

Input power factor ranges from 0.286 to 0.634 for conventional dimmers and from 0.804 to 0.813 for new-model dimmers.

e. Active power efficiency

For the three values of the fundamental output voltage between phase and neutral, the values of the input and output power factors are shown in Fig. 10.

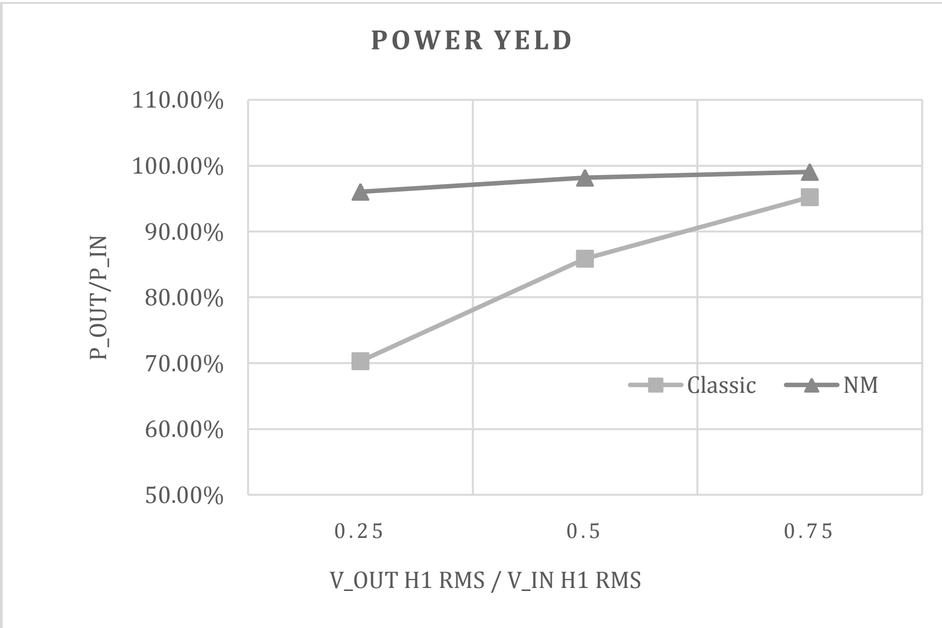

Fig. 10: Active power efficiency

Active power efficiency ranges from 70.30% to 95.19% for conventional dimmers, and from 96.05% to 99.05% for new-model dimmers.

IV. DISCUSSIONS

- The voltage and current output curves are consistent with theory. The output voltages and currents of the new model dimmer have quasi-sinusoidal curves.

- The variation in output voltage, supplied to the load, is obtained for both assemblies, and is quasi-linear for the new model dimmer, for alpha from 0 to 100%. This makes the converter ideal for industrial control applications.
- THD values for output voltage and output current are much lower for the new model dimmer than for the conventional one. This ensures longer life and greater energy efficiency for loads such as electric motors.
- Input current THD values are very low for the new model dimmer compared to the classic one. The new model dimmer will therefore pollute the electrical networkonlyslightly.
- At output, power factor values (phase shift between voltage and fundamental current) are close to 0.8, the value for a pure sinusoidal supply. But at the input, relative to the mains voltage, the power factor deteriorates for the classic dimmer (from 0.286 to 0.634) and improves for the new model dimmer (from 0.804 to 0.813). The high value of the power factor ensures high active power while reducing disturbance to the distribution network (also reducing the cost of reactive power compensation).
- For all these reasons, the active power efficiency of the new model dimmer is much better than that of the conventional dimmer.
- Generation of the pulse-width modulated (PWM) control signals for the new model dimmer is simpler and less costly than for the conventional dimmer. Power assembly costs are, however, higher for the new-model dimmer.

V. CONCLUSION

In summary, a new model of pulse-width modulation dimmer for three-phase star loads is proposed in this work. Simulation in Matlab Simulink has enabled to compare the performance of this dimmer with that of a conventional dimmer for supplying a three-phase, balanced, star-connected RL load. The new dimmer model is efficient and outperforms the conventional one in terms of energy efficiency, input and output harmonic distortion rate (voltage and current), power factor and RMS voltage variation. In addition, the control circuit is easier to implement, especially for control applications.

However, the cost of the power assembly is higher. In practice, the dimmer can be realized and used to supply variable power to industrial inductive loads. In the long term, the realization and large-scale use of this dimmer will contribute to the development of industrial automation and thus to the achievement of the ninth and twelfth Sustainable Development Goals, namely industry, innovation and infrastructure, and responsible consumption and production.

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