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Transfer Function and Transient Response Analysis of Active Inrush Current Limiting Circuit on P-MOSFET with Equivalent RLC Series Circuit Load of Inverter

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Abstract: Inrush current is a transient current surge when a piece of electrical equipment is turned on. One of the solutions is a P-MOSFET-based active inrush current limiter, which will be analyzed with KiCad software to analyze the transient response graph and a Python program to analyze the transfer function graph. From the observation, the circuit could reduce the inrush current amount which was initially ranging from 12mA – 12A to below 500nA, with a very low amount of ripple (under 100nA peak-to-peak). The transfer function graph from the RLC load represents its transient response graph, and the transfer function graph of the inrush current limiter with load creates a logarithm function.

Keyword: Inrush current, P-MOSFET, transient response, transfer function, ripple

INTRODUCTION

One of the main problems in the use of electrical energy in households is the inrush current generated by electrical appliances that contain reactive components. Examples include air conditioners, washing machines, refrigerators, etc. (Arief, 2018). Inrush current is an input current surge that occurs instantly and transiently when electrical equipment containing reactive components is first turned on. (Kusko & Thompson, 2007). Inrush current can cause problems because it can trigger current limiters such as fuses or circuit breakers so that the flow of electric current is cut off and makes electricity on the network go out. Inrush current is known to arise from several components, including capacitors and inductors/transformers. Capacitors, in an empty state, can be considered as a short circuit (short circuit, where the resistance of the component is very small) by the power source thus triggering a very large input current and causing an inrush current. Inrush current can also occur in transformer components, where the transformer when energized can cause a saturation effect on the core of the transformer which causes a surge in current. (Siagian, Jaya, & Nurhidayati, 2021).

There are several ways to overcome inrush current, one of which is by using a resistor as a current limiter in series with a load that has a large inrush current. However, this method has the disadvantage that the resistor will also share the voltage in addition to limiting the current, so it is not suitable for use against electronic devices that have a large sensitivity to the input voltage value. In addition, the resistance in the resistor will dissipate heat which is a power loss depending on the amount of current passing through it. Another way to limit the inrush current is to replace the resistor with an NTC (negative temperature coefficient) thermistor. NTC thermistors have high resistance when the temperature is low, and the resistance decreases as the temperature increases. (de Györgyfalva & Reaney, 2001). Assuming when the equipment has not been turned on the thermistor is still in a cold state, the thermistor will work optimally. The weakness of NTC thermistors is that the measurement accuracy at low temperatures is minimal and it is difficult to find equivalent components.

Based on these problems, another method is made in overcoming inrush current, namely by using P-MOSFET. P-MOSFET is one type of semiconductor made of metal oxide which has three legs, namely gate, drain, and source. MOSFET can work if the leg on the gate is given a voltage, so that it will connect the drain and source legs. MOSFET has a turn-on resistance value or turn-on resistance that varies (ON Semiconductor, 2014). When just turned on, the P-MOSFET has a large instantaneous resistance and will drop when normal so there is a delay in connecting the drain and source legs. (Okilly, Namhun, & Jeihoon, 2020). Based on these characteristics, MOSFETs can be used as inrush current limiters. When actively working, the P-MOSFET has a very low power loss. (Ong, Seki, Ko, & Hu, 1989). Thus, an inrush current limiting circuit using P-MOSFETs can be used as an input current surge limiter. Analysis of P-MOSFET testing as an inrush current limiter is carried out on the inverter, where the inverter has a very large input current when it is first turned on. The inverter has a main component in the form of a transformer as a voltage booster and also several capacitors with large sizes as filters or dampers of output voltage ripple. (Jamali, Mirzaie, & Gholamian, 2011). Simulation tests on the inverter were carried out using the equivalent RLC circuit of the inverter, then circuit analysis was carried out using KiCad software and the Python program. (Moradi & Madani, 2018). KiCad is used to display a graph of current against time to analyze the transient response of current surges that occur, while the Python program is used to create a transfer function graph. (Virtanen et al, 2020).

METHOD

The parameters used in this study are as in Table 1 below. The parameters in question are the parameters of the RLC equivalent circuit in the inverter and also the parameters of the inrush current limiting circuit. The RLC equivalent circuit in the inverter is given a resistor value of 1Ω, 10Ω, 100Ω, and 1KΩ while the inductance value is given a value of 1H, then for the capacitance value is given a value of 1F. The inrush current circuit in the simulation is given R1 and R2 values of 250Ω and 1KΩ, while the capacitance is given a value of 10nF.

Table 1. Circuit Parameters

Equivalent circuit			Inrush current limiting circuit		
R	**L**	**C**	**R_1**	**R_2**	**C_1**
1 Ω, 10 Ω, 100 Ω dan 1 kΩ	1 H	1F	250 Ω	1kΩ	10nF

Figure 2 below is a circuit for simulating inrush current along with loads that are varied from 1 Ω, 10 Ω, 100 Ω and 1 kΩ. The main component of this design is a MOSFET with type P, where the source leg (S) is connected to a 12V DC voltage source. Then for the drain leg (D) is connected to a load circuit in the form of resistor, inductor, and capacitor components. The gate leg (G) is connected to a 1KΩ resistor and connected to the ground so that this P-MOSFET can be active and work.

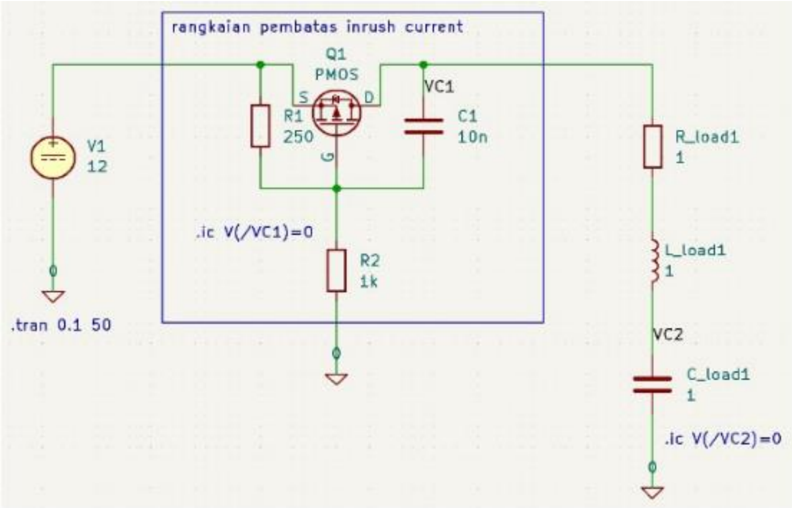

Figure 2. Inrush current limiting circuit with load

The current flowing in R_2 can be written as in equation (9) below.

$$i_{(t)} = \frac{Vin}{R_2} e^{-at} \tag{1}$$

While the Laplace transformation is known as equation (10) below.

$$e^{-at} = \frac{1}{s+a} \tag{2}$$

To get good results, the LTI method is used to obtain the transfer function as equation (11) below as the unit transfer function used to obtain the appropriate response time..

$$TF = \frac{s}{s^2 + s + 1} \tag{3}$$

RESULT AND DISCUSSION

From the resulting graph, the amount of current flowing with power dissipation in component R of each RLC circuit at points t every 5 s interval starting from t = 0 to t = 50 s is as shown in Table 2 below, which uses RLC series circuit specifications with values of 1Ω, 1F and 1H.

Table 2. Current and Power Dissipation in RLC Series Circuits with Values R = 1, L = 1, and C = 1

t (s)	Current flowing (A)	Dissipation power (W)	Difference of dissipation power with the previous point t
0s	12	144	-
5s	-898,929m	808,073m	-99,4388%
10s	-26,1637m	684,539µ	-91,3019%
15s	7,71634m	59,5419µ	-91,3019%
20s	-296,775µ	88,0754n	+47,9217%
25s	-34,1778µ	1,16812n	-98,6737%
30s	4,11805µ	16,9583p	-98,5482%
35s	-21,0292n	442,227[a]	-99,9974%
40s	-26,6862n	712,153[a]	+60,3595%
45s	1,78383n	3,18205f	-99,5532%
50s	71,8021n	5,15554f	+16.191,9%

Then Table 3 shows the current and power dissipation in the RLC circuit with a value of 10Ω, 1F, 1H. Then Table 4 shows the current and power dissipation in the RLC circuit with a value of 100Ω, 1F, 1H and finally Table 5 shows the current and power dissipation in the RLC circuit with a value of 1kΩ, 1F, 1H.

Table 3. Current and Power Dissipation in RLC Series Circuits with Values R = 10, L = 1, and C = 1

t (s)	Current flowing (A)	Dissipation power (W)	Difference of dissipation power with the previous point t
0s	1,2	14,4	-
5s	731,605m	5,35246	-62,8301%
10s	441,477m	1,94901	-63,5866%
15s	266,405m	709,716m	-63,5858%
20s	160,761m	258,441m	-63,5853%
25s	97,0097m	94,1088m	-63,5860%
30s	58,5395m	34,2687m	-63,5861%
35s	35,3250m	12,4786m	-63,5860%
40s	21,3166m	4,54397m	-63,5859%
45s	12,8634m	1,65467m	-63,5854%
50s	7,7622m	600,252µ	-63,7238%

Table 4. Current and Power Dissipation in RLC Series Circuits with Values R = 100, L = 1, and C = 1

t (s)	Current flowing (A)	Dissipation power (W)	Difference of dissipation power with the previous point t
0s	120m	1,44	-
5s	114,158m	1,30320	-9,5%
10s	108,59m	1,17918	-9,52535%
15s	103,294m	1,06697m	-9,51593%
20s	98,2555m	965,414m	-9,51817%
25s	93,4632m	873,537m	-9,51685%
30s	88,9044m	790,399m	-9,51739%
35s	84,568m	715,175m	-9,51722%
40s	80,4432m	647,111m	-9,51711%
45s	76,5196m	585,525m	-9,51707%
50s	72,7873m	529,799m	-9,51727%

Table 5. Current and power dissipation in RLC series circuit with R=1k, L=1, and C=1.

t (s)	Current flowing (A)	Dissipation power (W)	Difference of dissipation power with the previous point t
0s	12m	144m	-
5s	11,9402m	142,568m	-9,94444%
10s	11,8806m	141,149m	-9,95315%
15s	11,8214m	139,745m	-9,94694%
20s	11,7624m	138,354m	-9,95384%
25s	11,7037m	136,977m	-9,95273%
30s	11,6454m	135,615m	-9,94328%
35s	11,5873m	134,266m	-9,94728%
40s	11,5295m	132,929m	-9,95784%
45s	11,472m	131,607m	-9,94516%
50s	11,4148m	130,298m	-9,94628%

Based on the graph shown, the current in the capacitor is zero at t = 0, while the current in the resistor and inductor is maximum at t = 0. The current in the capacitor increases and saturates at time t around 1.0 ms. Thus, it can be concluded that the capacitor experiences a transient response in the form of inrush current in the interval 0 - 1.0 ms, while the resistor and inductor receive instantaneous current since t = 0. In the simulated RLC series circuit, the RLC series circuit with a value of R = 1 looks underdamped. This can be seen from the oscillations until the current in the circuit drops to a negative value relative to the y-axis, then rises again to the positive y-axis, then drops to the negative y-axis, and rises again to the positive y-axis, and so on until the point of stability. The transient response graph for other R values is critically damped, which can be seen from the consistently decreasing current value since saturation.

In Figure 3 below is the transfer function graph of the RLC circuit with variations in the value of R. Based on the graph displayed, it can be seen that in the series RLC circuit with R = 1 the graph is underdamped and oscillates twice before finally stabilizing at position x = 14. The graph has a minimum y value of -0.1 < y < 0 and a maximum y of 0.5 < y < 0.6. While the graph of the series RLC circuit with other values looks like an impulse graph whose value starts from the maximum value at position x = 0, then drops with a negative exponential function. At R = 10, the graph stabilizes at position x = 70 (+400% of R = 1), has a minimum y value close to zero and a maximum y value of 0.08 < y < 0.1 (-84% < percentage difference with R = 1 < -67%). At R = 100, the graph stabilizes at position x = 700 (+1000% of R = 10), has a minimum y value close to zero and a maximum y value of 0.008 < y < 0.01 (percentage difference with R = 10: -90%). In the R = 1k graph, the graph stabilizes at position x = 7000 (+1000% of R = 100), has a minimum y value close to zero and a maximum y value of 0.0008 < y < 0.001 (percentage difference with R = 100: -90%). Thus, it can be concluded that if the transient response graph is underdamped and experiencing oscillations, the level of damping and oscillations experienced are also reflected in the transfer function graph. Meanwhile, if the transient response graph is critically damped, then the transfer function graph will be in the form of an impulse function with a large impulse (in the direction of the y-axis) which is getting smaller and the large frequency domain s towards stability (in the direction of the x-axis) which is getting bigger along with the increasing component R (large damping) in the range of R = 1 - 1k ohm.

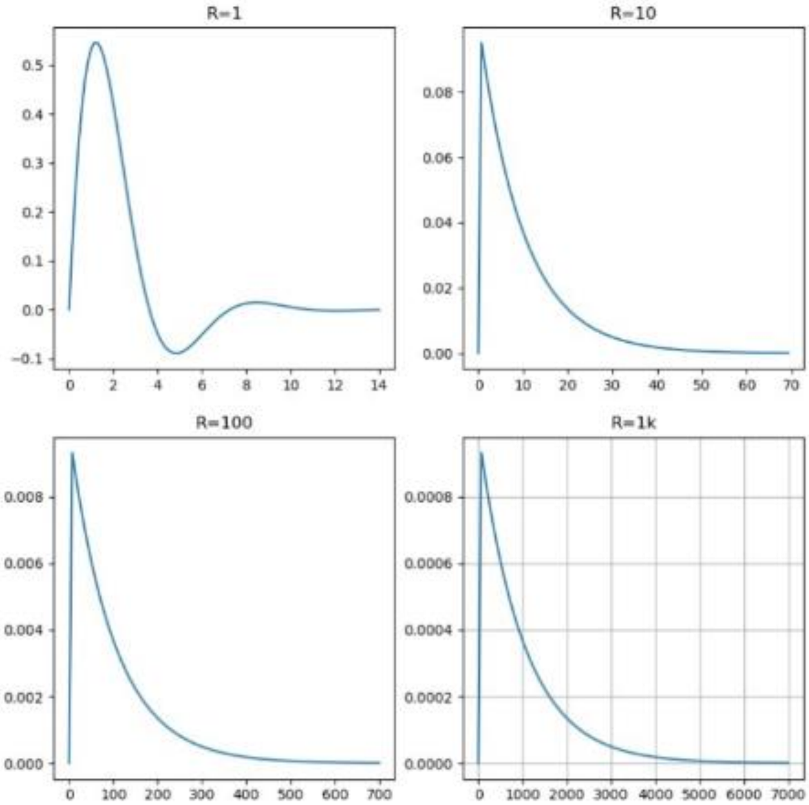

Figure 3. Transfer Function of RLC Circuit with Variation of R Value

Based on the graphs displayed in Figure 4 to Figure 6 below shows the response results of each load used. It can be seen that the transient response of the inrush current limiting circuit along with the load produces ripple or oscillation at the output, but the resulting ripple is very small to below 100nA peak-to-peak in the circuit with R load 1, 10, and 100, and even smaller in the circuit with R load 1k. The inrush current value can be suppressed to below 500nA on average, so the power dissipation released by the resistor at t=0.

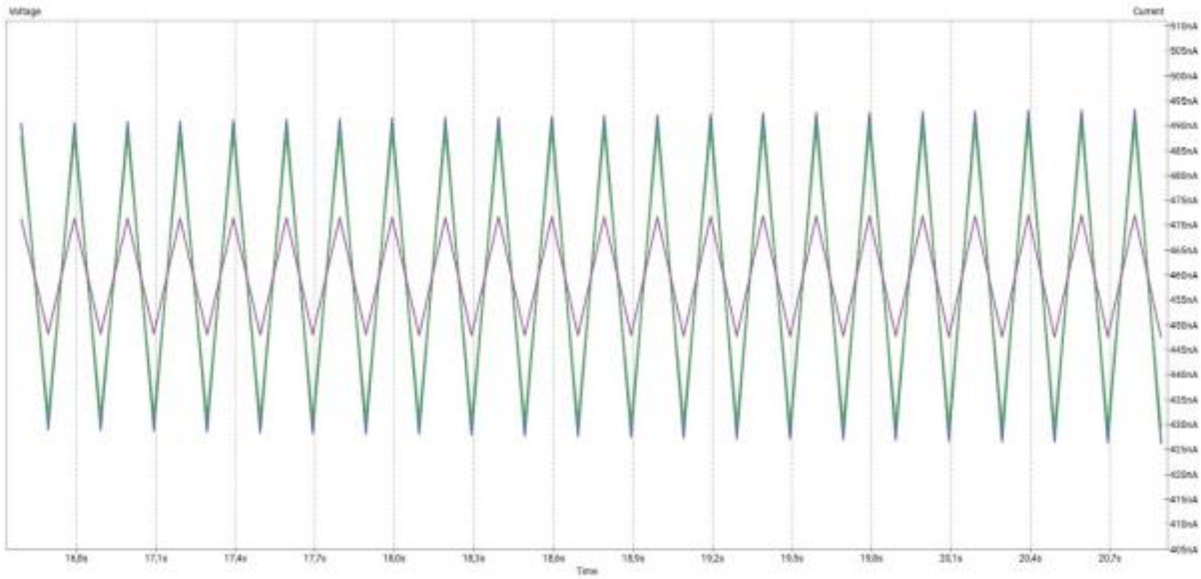

Figure 4. System Transient Response Shape at Component C Load, in the Form of Ripple

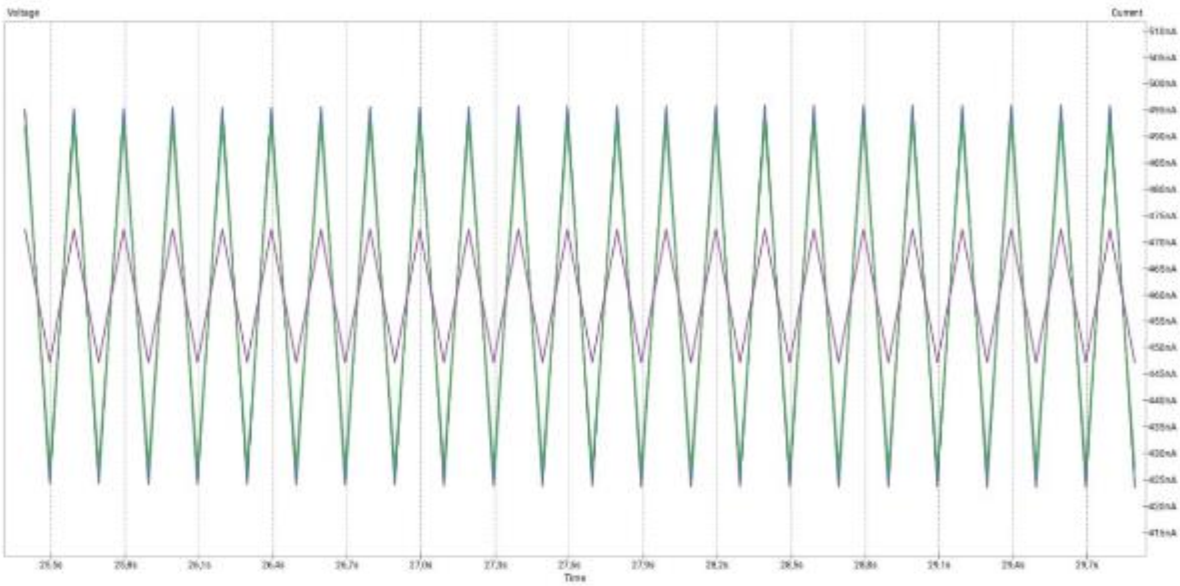

Figure 5. System Transient Response Shape at Component L Load, in the Form of Ripple

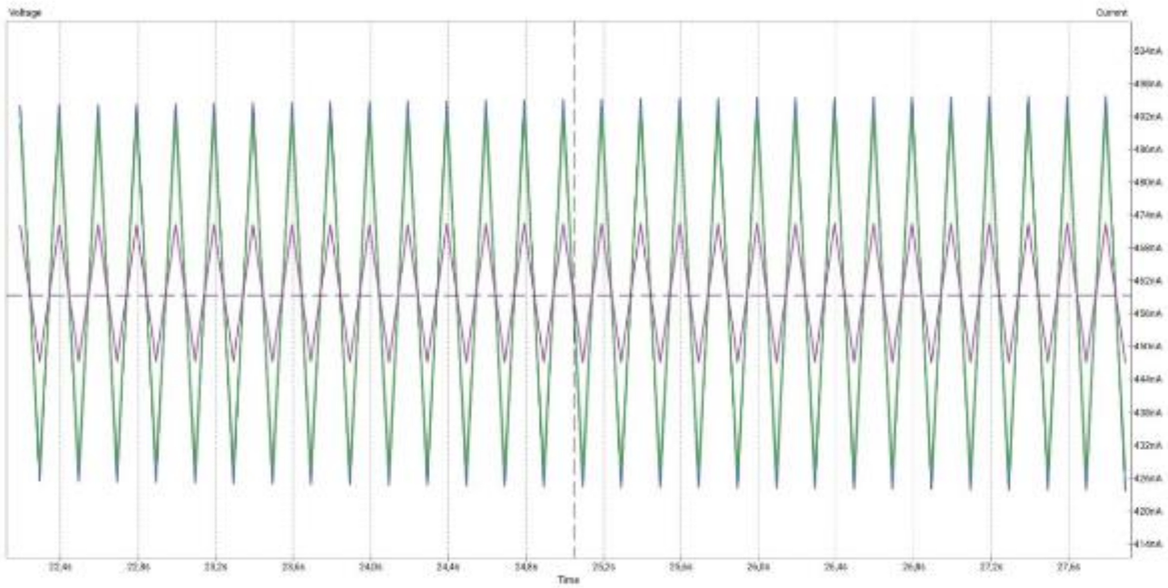

Figure 6. System Transient Response Shape on Load Component R, in the Form of Ripple

From the graph shown, the transient response of the inrush current limiting circuit along with the load produces a very small ripple to below 100nA peak-to-peak with R load 1, 10, 100 getting smaller at 1k. The inrush current value can be suppressed until the average reaches below 500nA.

CONCLUSIONS

The inrush current limiting circuit is effective in reducing the inrush current on the equivalent RLC series circuit load of the inverter (from 12mA-12A to about <500nA and the circuit with relatively low resistance tends to produce ripple, but the observed ripple is still small (<100nA peak to peak).

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