

# Soft start optimization using NTC resistors in fault managed power systems

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**Abstract**—Inrush current limiting methods using Negative Temperature Coefficient (NTC) resistors in power converter circuits are prominent choices in device and system protection schemes. In this paper, a newly developed equipment protection algorithm is introduced, which involves the temporary inclusion of NTC resistors in fault-managed power circuits. The circuit configuration is robust and highly energy-efficient as it maximizes startup capabilities, using the NTC resistor’s self-heat feature to soft start larger loads by fully utilizing the NTC resistor’s energy capacity while still being efficient by bypassing the NTC resistor afterwards. The control algorithm is developed and applied in a real-world Packet Energy Transfer (PET) system. Simulation models were validated with experimental results for a performance study of the soft start circuit.

**Index Terms**—NTC, System protection algorithm, Inrush current control

## I. INTRODUCTION

In recent years, with the substantial growth of power electronic circuits and systems in a wide range of applications including energy conversion, renewable energy integration, grid connection, electric transportation systems, and modern power delivery methods [1]–[3]; system protection and human safety issues have emerged to a large extent. A major focus in existing research and literature available has been the control and protection of the power electronic system with an emphasis on inrush current mitigation [4]–[9]. It is even more crucial for Fault Managed Power (FMP) systems, particularly Packet Energy Transfer (PET) circuits that need more accurate and precise inrush current control as additional equipment protection features are introduced in such systems. In a PET system, a PET transmitter sends power to a PET receiver in pulses that have a duration of milliseconds in order to stay below the level that could result in a fire or bodily injury. To determine if a subsequent pulse should be sent, the PET protocol employs a unique fault protection algorithm to detect any line-to-line or line-to-earth human touch distinct from the load current as well as poor connections with abnormally high resistance that could result in a fire. By utilizing sophisticated soft start techniques, PET systems can

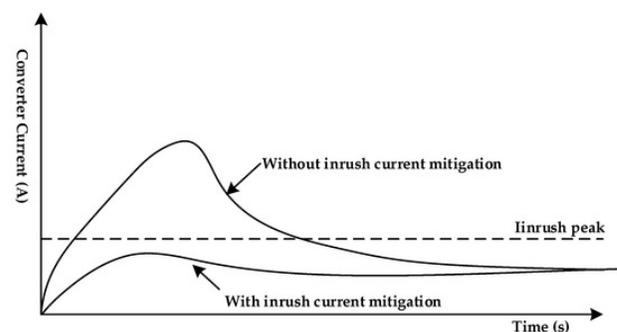


Fig. 1. Inrush current at soft start state

be integrated with a wide variety of load devices without the need to design the system specifically for each and every load device, many of which are unknown at design time. In most DC-DC converter applications, thermistors (Positive and/or Negative Temperature Coefficient) and MOSFETs are popular choices; and the initial spike of current can be mitigated by using various existing schemes (See Fig.2 [10], [11]). Using an NTC resistor over a PTC resistor has the advantage of minimizing the voltage difference between the supply and the load by the end of soft start, thereby minimizing the current spike when direct connecting. An NTC resistor also allows for simplified controls, greater design tolerances, and less EM noise when compared to typical soft start techniques using MOSFETs. Care must be taken when utilizing thermistors, as fracturing may occur due to stress from thermal gradients created by sudden inrush current [12].

In this paper, a novel circuit protection feature for limiting the inrush current during startup in a PET system by utilizing the self-heat effects of the NTC resistors is presented. In section II, the mathematical model for self heating and cooling process of the NTCs is described at first, and in the later part a step-by-step control algorithm developed for temporary inclusion of the NTC resistor is discussed. In the following section, a basic PET circuit with a soft start scheme using an NTC resistor is presented. The circuit is analyzed and

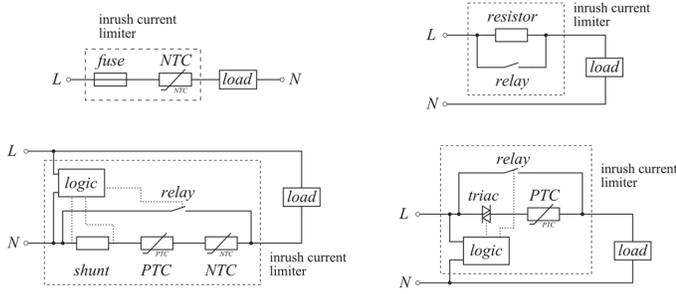


Fig. 2. Existing control schemes

simulated. The simulated results are then validated using experimental results from the identical test circuit. Finally, the summary of the study is presented in section IV. The proposed protection scheme has unique features to offer to the existing and upcoming power electronic solutions for different power delivery systems.

## II. MODEL DEVELOPMENT

### A. Mathematical Model

NTC resistors have the unique property of variable resistance that is temperature-dependent. With the increase in device temperature, the NTC resistors tend to decrease their resistance values. The self-heating property of NTC resistors are best described by:

$$P_{el} = V \cdot I = \frac{dH}{dt} = \delta_{th} \cdot (\theta - \theta_A) + C_{th} \cdot \frac{d\theta}{dt} \quad (1)$$

Where,  $P_{el}$  is electrical power applied,  $V$  is the instantaneous value of the NTC resistor voltage,  $I$  is the instantaneous value of the NTC resistor current,  $\frac{dH}{dt}$  is the change in stored thermal energy with time,  $\delta_{th}$  is the dissipation factor of the NTC resistor,  $\theta$  is the instantaneous temperature of the NTC resistor,  $\theta_A$  is the ambient temperature,  $C_{th}$  is the heat capacity of the NTC resistor,  $\frac{d\theta}{dt}$  is the change in temperature with time. This does assume that the dissipation constant and heat capacity do not change with temperature. From this self-heat equation, it can be deduced to the following heat equation:

$$H(t_2) = \int_{t_1}^{t_2} P_{el}(t) dt + H_o \quad (2)$$

Solving for the self-heat equation assuming a constant dissipation factor and a constant thermal heat capacity derives the following equation for temperature:

$$\theta_c(t) = e^{-t/\tau_{th}} \cdot \frac{1}{C_{th}} \int_0^t e^{t/\tau_{th}} \cdot P_{el}(t) dt + (\theta_o - \theta_a) \cdot e^{-t/\tau_{th}} + \theta_a \quad (3)$$

The cooling process of the NTC resistor can be described as:

$$\theta(t) = \theta_f + (\theta_0 - \theta_f) \cdot e^{-t/\tau_c} \quad (4)$$

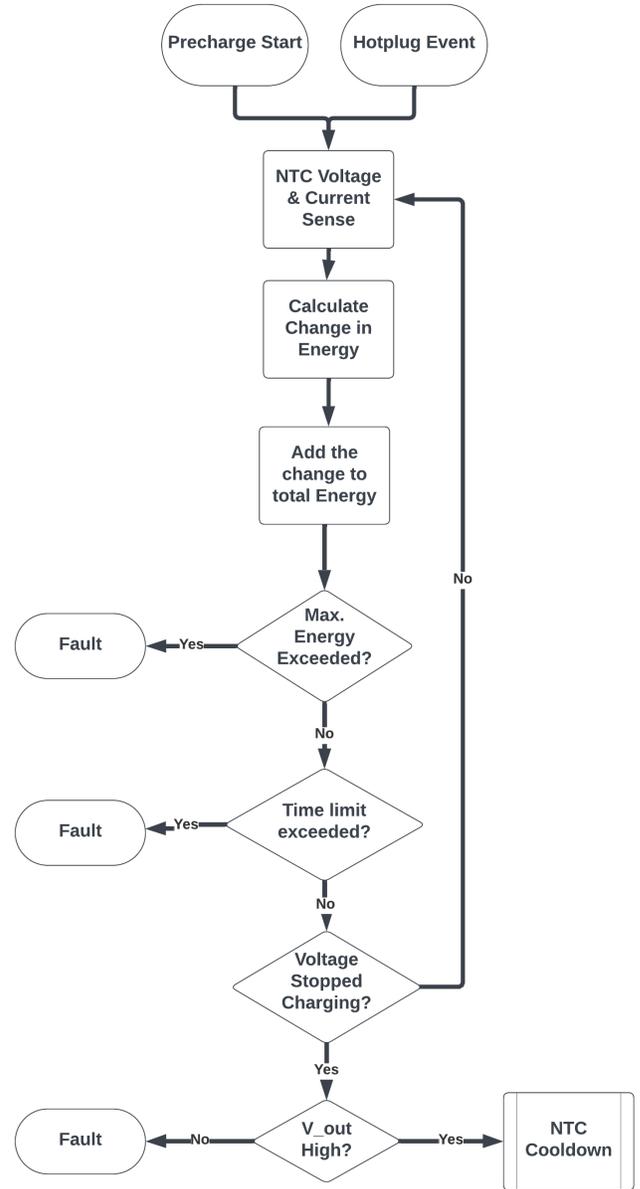


Fig. 3. Flowchart for the soft start algorithm

### B. Algorithm Development

1) *Step I :Energy Accumulation:* While the NTC resistor is in the circuit, the electrical energy through the NTC resistor is used to accumulate the energy level of the NTC resistor to check if it has exceeded the rating.

This limit ensures the NTC resistor does not fail per its manufacturer's specifications, and determines a part of the limitations of what can be supported by the system using this NTC resistor. The basis for this largely uses equation 2 but uses a trapezoid approximation for the integration since the measurements are taken at regular, small intervals:

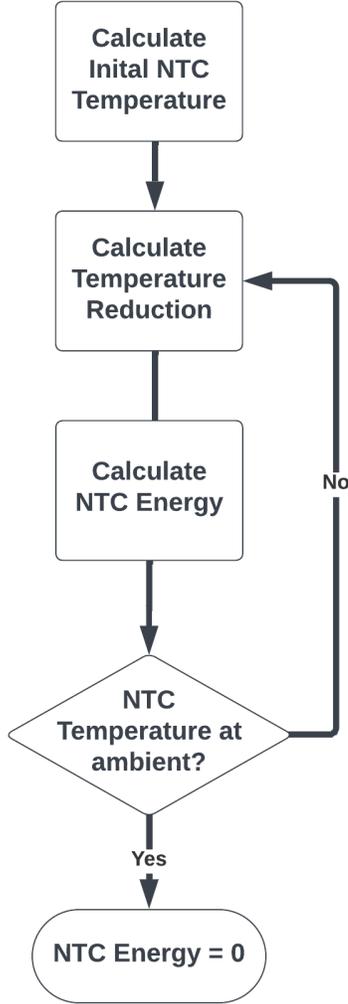


Fig. 4. Flowchart for the cooldown algorithm

$$H(t_2) = \frac{(P_{el}(t_1) + P_{el}(t_2))}{2} \cdot (t_2 - t_1) + H_o \quad (5)$$

For the very first iteration,  $H_0$  is defined as the energy remaining that has not dissipated from a previous run, or 0 if this is the first run. Based on thermodynamic studies and failure modes of the NTC resistor, there is no de-rating to pre-load this energy value based on the ambient temperature.  $H(t_2)$  becomes the  $H_0$  in the next iteration. This value of  $H(t_2)$  is compared against the maximum recommended energy of the NTC resistor per the manufacturer's specifications and, if it has exceeded it, decides to either immediately turn on its main FET to bypass the NTC resistor for a successful end of soft start, or it faults out.

2) *Step II : Direct Connect*: After energy accumulation, direct connect is evaluated and possibly executed. Direct connect is where the NTC resistor becomes bypassed to directly connect bus voltage to the load without a current limiting NTC

resistor. As described previously, this can happen when the energy accumulation has reached a maximum; but it can also be triggered when the voltage has stopped rising by a sufficient rate. In both cases, the output voltage is then compared to the bus voltage to see if it is sufficiently high.

3) *Step III: Cooldown process of NTC resistor*: Immediately following the end of the energy accumulation algorithm and possible direct connect—regardless of success—the present temperature of the NTC resistor is calculated. This is based on the following equation

$$H_2 - H_1 = C_{th} \cdot (\theta_2 - \theta_1) \quad (6)$$

Solving for  $\theta_2$  yields:

$$\theta_2 = \frac{H_2 - H_1}{C_{th}} + \theta_1 \quad (7)$$

Using  $H_2$  as the final  $H(t_2)$  from 5,  $H_1$  as the very first  $H_0$  used in the first iteration of 5, and  $\theta_1$  as the temperature of the NTC resistor of the very first iteration of 5,  $\theta_2$  will yield the temperature of the NTC resistor at the end time of the energy accumulation algorithm. From here, the temperature is allowed to decay based on the thermal cooling constant using equation 4, where  $\theta_f$  is the live-updated ambient temperature  $\theta_a$ , and  $\theta_0$  is initially the  $\theta_2$  calculated in equation 7. For each time step, the  $\theta(t)$  is calculated using  $t$  as the time elapsed since the last calculation (typically a regular constant interval). This  $\theta(t)$  becomes the  $\theta_0$  for the next iteration, with the  $t$  remaining the regular constant interval for the time elapsed between calculations. At each step, the energy is re-calculated as  $H_2 - H_1$  using equation 6, plugging the live ambient temperature in for  $\theta_1$  and the NTC resistor temperature calculated for this loop as  $\theta_2$ . This is concluded when the energy reaches 0; however, hot plug is still allowed to be attempted at any time, and a fresh soft start attempt from an off state is allowed once the energy drops below a minimum threshold (See Fig. 3).

### III. CIRCUIT ANALYSIS & RESULTS

The circuit illustrated in Fig. 5 shows a general schematic of the PET system with a soft start circuit using an NTC resistor ( $R_1$ ). At first, the switch  $S_2$  is closed and  $S_1$  is kept open so the initial current to charge the capacitor ( $C_1$ ) flows through the NTC resistor. The soft start control algorithm executes from the start and checks the status of the system at a regular time interval (in the order of milliseconds). Once the capacitor is charged to the optimum level, the states of the switches are toggled to isolate the NTC from the main circuit. At this point, the cool down algorithm comes into play. The scheme continues as long as the system is up and running until any fault occurs.

The circuit was simulated using a DC source; the simulation results are shown in Fig.6. The input voltage, the output voltage and voltage across the NTC resistor are measured during operation of the test circuit, both in simulation and in experimental setup. The simulated results are validated using the identical test setup in VoltServer, Inc's test lab where

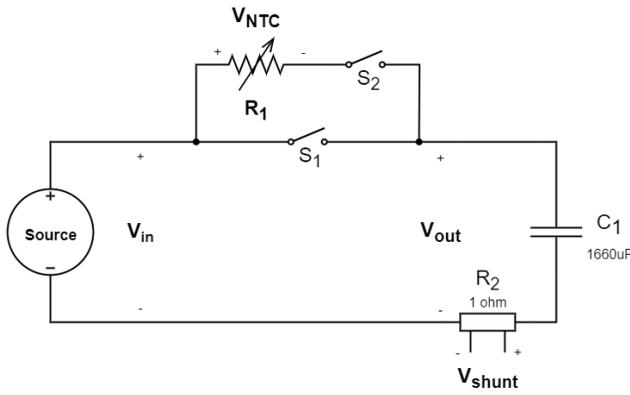


Fig. 5. Basic PET configuration with soft start circuit

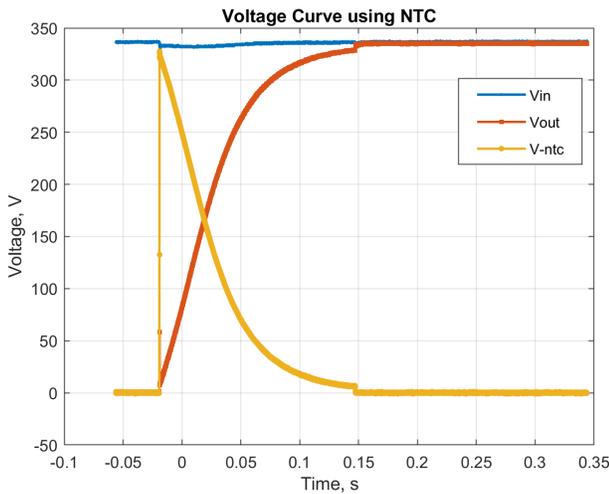


Fig. 6. Simulated waveform from PET with soft start circuit

the soft start circuit is embedded into the PET system. The measurements are displayed on a mixed signal oscilloscope which is shown in Fig.7. The test results from the test circuit are compared with the simulated data to make sure the circuit and the control scheme operate as described.

At start up, the voltage across the NTC resistor is very high due to it's high resistance value, but it starts to exponentially decay over time as the heat increases and in turn, the resistance decreases. On the other hand, the load voltage ( $V_o$ ) has increased steadily over time and reached the rated voltage level. At this point, the soft start circuit is disconnected and direct connection from source for the load circuit was established. During this transition, voltage and current measurements at the NTC resistor are sampled and checked with the algorithm parameters to ensure the successful start up operation with all the safety conditions achieved through this process. In the event of a fault or failure, the NTC resistor would have disconnected the load and protected the circuit from a high inrush current. The temporary but crucial presence of the NTC resistor in the circuit not only secures the safety of the operation, but also protects the NTC resistor itself from device



Fig. 7. Oscilloscope capture from the test circuit

failures due to excessive heat accumulation during steady state operation.

#### IV. CONCLUSION

In summary, this paper describes the novel equipment protection features of a circuit control algorithm developed using the thermal properties of an NTC resistor. The mathematical models were discussed and used in the algorithm development and depicted via a flowchart in simple terms. The test circuit was simulated and tested at a laboratory facility to validate the results of the proposed circuit operation. In safety-critical systems, such as fault-managed power systems, it is highly important to ensure protection of the equipment and the environment, and the addition of a soft start circuit with a circuit protection algorithm is a step forward to achieve this goal. In the future, more extensive studies can be conducted using similar algorithms for more complicated systems with different load conditions.

#### V. ACKNOWLEDGEMENT

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