White Paper

Transient Stability of Remote DC Powering of Optical Network Units

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Abstract. *Network powering of optical network units (ONUs) in fiber in the loop (FITL) and fiber to the curb (FTTC) architectures is finding increasing use. The nonlinear dynamics of startup and short-circuit recovery for network powering of these architectures are discussed with the aid of state-plane analysis.*

1. Introduction

Network powering of optical network units (ONUs) provides dc electrical power to two or more ONUs over copper twisted-pair connections [1]. Distances between an ONU and the remote powering system (RPS) can range from tens of meters up to three or four kilometers and more. An ONU load characteristic is an essentially constant-power load. A dc-to-dc converter at the ONU input converts the dc input voltage to a regulated voltage used by internal ONU loads.

Safety issues, which are documented in regulatory agency specifications, such as the IEC 950 (adopted in EN 60950, National Electric Code (NEC) and National Electric Safety Code (NESC), dictate a maximum network dc voltage. In the U.S., this maximum is presently 140Vdc, and thus the voltage produced by the RPS is limited to 140Vdc maximum. Of course, to reduce corrosion as much as possible, the actual voltage polarity applied to the copper twisted pairs is negative. Further specifications identified in the agency regulations mentioned earlier also limit the volt-amperes in a twisted pair to 100-VA or less.

Several situations are considered here. First, the startup characteristics of the RPS-ONU system are studied, where startup refers to a startup of an ONU which has been unpowered for a sufficiently long period such that initial conditions are all zero. A second scenario studied occurs following removal of a short circuit at the ONU end of the RPS-ONU twisted pair. During this short circuit situation, an ONU voltage of 0V is present. Following removal of the short, it is expected that the ONU voltage rises and attains an ONU steady-state voltage within the normal ONU input range. Perhaps the most common dynamic for the RPS-ONU powering system is a step-change in the ONU power level. Step changes in ONU power demands are used to examine the resulting system dynamics. It is seen that ONU capacitance and the inductance of the RPS-ONU twisted-pair loop can have strong influences on the satisfactory performance of the powering system. Step changes in ONU power demands occur when the ONU is supplying varying telephony loads with POTs lines changing among ringing, on-hook, and off-hook. Other ONU power step changes occur during ONU startup, when the ONU power demand is initially minimal, and increases significantly when the fiber-optic transceivers synchronize with the host digital terminal (HDT) or remote terminal (RT). Two types of step-load changes are examined, those which are initiated from an ONU in open circuit conditions and those which start with an ONU operating at some nonzero power level.

Interestingly enough, system variables can be concocted which in each of the four scenarios presented, startup from zero initial conditions, startup from a short-circuit, step change in load starting from an open circuit and a step change in load starting from a nonzero power level, it is possible to concoct system variables which lead either to unstable operation, or operation at an undesired and circuit conditions conditions, it is possible to provide a sample system which leads to operation at undesired operating points or oscillatory operation. At the RPS, the power supply is a 100-VA supply, but over longer RPS-ONU loops the voltage drop across the loop can be as much as one-half the source voltage, and thus up to one-half the power from the RPS source is delivered to the copper, twisted pair loop rather than the ONU. Thus, because of the power consumption on the RPS-ONU copper twisted pair, the volt-ampere or watts (this is a dc source) available at the ONU is less than the volt-amperes available at the RPS source. Thus, although the RPS is a 100-VA source, the power available at the ONU end of a particularly long RPS-ONU loop could be as low as 50W.

2. System Equivalent Circuit

An RPS-ONU powering connection is commonly made over copper twisted pairs, with several different wire gauges in common use, each with different resistance values. The parasitic inductance of the copper pairs is independent of the resistance of the RPS-ONU connection. At the input to the ONU, a energy-storage capacitor is present to provide filtering which allows for short interruptions of the current into the ONU without a significant change in ONU voltage. Figure 1 contains a schematic of the RPS-ONU system model which is used in this study.

It is interesting to note the resemblance of this circuit with the power-processing systems found in the distributed powering architectures of microprocessor systems [2]. These microprocessor systems distribute a dc bus voltage to local dc-to-dc converters, each of which has a constant-power load characteristic identical to the ONUs discussed here. An L-C filter, similar to inductance L_W and ONU capacitance C_{ONU} of Fig. 1, is located between these local dc-to-dc converters and the dc bus. Large numbers of researchers have sought to offer tractable, easy-to-use, salient design techniques to ensure stability, yet such a technique has remained elusive. In these microprocessor systems, efficiency is paramount, and thus power losses in the dc bus are minimized by designing bus resistance to be as low as possible. Losses arising from the copper twisted pairs in the RPS-ONU system can amount to as much as 50 percent of the output power and are accepted since reduction of these losses either requires dedication of more copper pairs, or using larger wire gauge in the copper pairs, neither of which is cost effective.

3. ONU Input Characteristics

Over longer RPS-to-ONU distances, the increased resistance of the longer copper twisted pair produces a lower ONU input voltage, and because of the constant-power ONU load characteristic, this lower ONU input voltage is accompanied by a larger ONU input current; input voltage to the ONUs is thus varies with RPS-ONU loop length, typically ranging from 140V for ONUs very close to the RPS, to 80V for an ONU located far from the RPS. At the ONU, an input dc-to-dc converter provides the internal ONU electronics with a constant, regulated voltage. Within the ONU input voltage range, 80V to 140V, the ONU presents a constant-power load. Based on the maximum power transfer theorem, maximum power is transferred to the ONU at an ONU voltage of one-half the open-circuit source voltage. Small-signal stability analysis shows that any equilibrium at an ONU input voltage less than one half the source voltage is unstable. Thus, since operation below one half the RPS source voltage cannot be stable, and to limit current flow in the RPS-ONU twisted pair loop, most ONUs have a low-voltage disconnect (LVD), which is the voltage below which the ONU disconnects from the input dc voltage. Thus, an ONU input characteristic appears as an open-circuit at voltages below V_{LVD} and as a constant-power load above V_{LVD}. These characteristics are seen in Fig. 2 at three different ONU power levels.

4. RPS Source Characteristics

The dc voltage sources in an RPS are volt-ampere limited sources as mandated by National Electric Code (NEC), Bellcore TA-1500, and IEC 950 (adopted in EN 60950). For the purpose of the analyses here, the volt-ampere limited sources are modeled as a current-limited source. Approximating the source as a current-limited in place of volt-ampere limited causes some changes in the amplitudes of the ONU-RPS system dynamics, although the characteristics of these responses are the same for either source model.

State space analyses [4] are graphical presentation of system dynamics, and can be used for both linear and nonlinear systems. The graphical techniques are most tractable for second-order systems because the state space is a two-dimensional state plane which can be plotted on a two-dimensional x-y plot. The variables plotted in a state space are the state variables which related to the energy content of the system. In our system, Fig. 1., the capacitor voltage and inductor current are the most logical choices for the state variables. The dc operating points in the state plane can be characterized as stable or unstable.

In preparation for presenting the dc operating points in the state plane, the dc load lines of the load (ONU) and source (RPS) are plotted simultaneously to produce candidate equilibria (singularities) which can be examined for stability. Since the RPS and ONU are not directly connected, but are interconnected with copper twisted pairs with resistance R_W, either the load line of the RPS source or the ONU loads must include the RPS-ONU resistance. Here the copper-pair resistance is associated with the RPS source such that the RPS characteristics seen in Fig. 3 incorporate the resistance R_W of the copper twisted pairs connecting the RPS to the ONU. In the longest possible RPS-ONU distance, one-half the source voltage is dropped across the copper resistance R_W and thus the ONU voltage V_{ONU} is one half the open-circuit source voltage. This is seen in Fig. 3 with copper resistance $R_{W,max}$ reducing the ONU voltage to the LVD voltage, V_{LVD}.

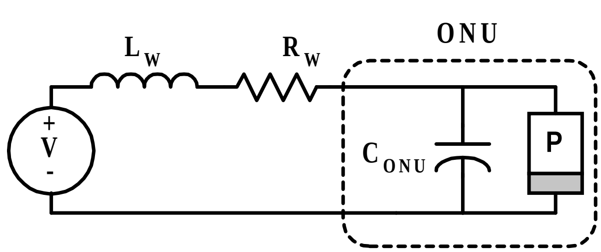

Figure 1. Equivalent circuit of RPS-ONU system. The rectangle enclosing the letter "P" represents the constant-power load of the ONU. Inductance L_W and resistance R_W represent the characteristics of the copper twisted pairs which interconncet the RPS and ONU.

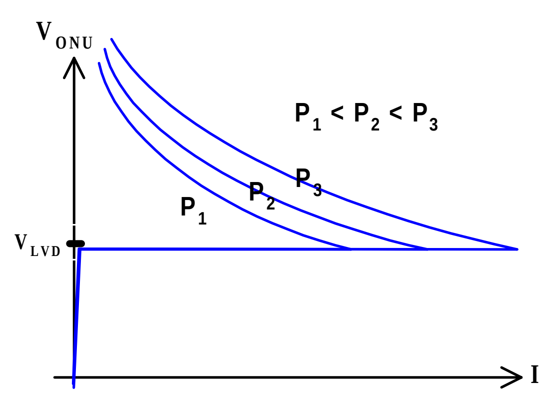

Figure 2. Graph of ONU V-I characteristics for three different ONU power loads. Higher ONU powers are characterized by a larger V-I product and are located higher and to the right on V_{ONU}-versus-I plane.

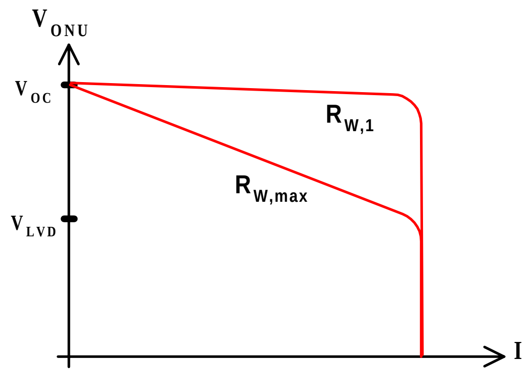

Figure 3. Combined characteristics of current-limited RPS source and copper-pair winding resistance R_W. Longest possible RPS-ONU line shown as $R_{W,max}$ while characteristics from a short RPS-ONU distance is seen with $R_{W,1}$.

5. Combined RPS and ONU Characteristics

Plotting the dc characteristics of the combined RPS and twisted pair resistance with the ONU characteristics produces intersections at which the V-I characteristics of each are simultaneously satisfied. Although the dc V-I characteristics of the RPS source and ONU loads overlap, these dc operating points must be examined to learn if they are stable or unstable equilibria. An example RPS characteristic is plotted with an ONU characteristic in Fig. 4.

Three equilibria must be examined in Fig. 4. Figure 4 illustrates the situation where the 100-VA source capacity is reduced in the copper pairs carrying power from the ONU to the RPS. In Fig. 4, because of losses in R_W, within the ONU voltage range between points 2 and 3, the ONU-load volt-ampere demand is larger than the volt-amperes arriving from the RPS source. If the volt-amperes which arrive from the RPS source over the twisted pair exceed the load volt-amperes, then the characteristics appear as in Fig. 5.

Examination of the three equilibria in Fig. 4 reveals that point 3 is a stable equilibria. Although point 3 is a stable operating point, it is *not* a desired operating point, as the ONU voltage is equal to V_{LVD}. This stable equilibrium at point 3 is quite a problem for short-

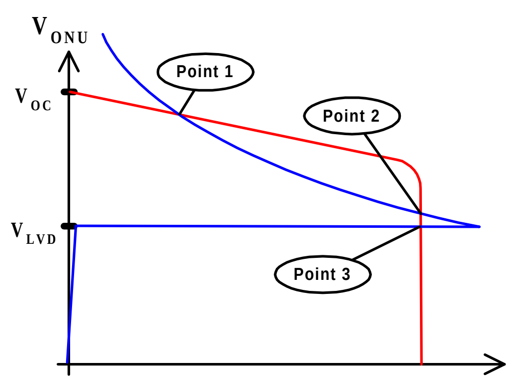

Figure 4. Combined RPS and winding resistance plotted with ONU load characteristics.

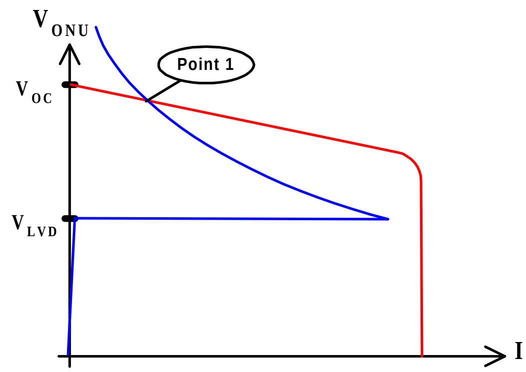

Figure 5. Same data as Fig. 4 with lowered ONU power load. Note absence of euquilibria at points 2 and 3.

circuit recovery of an ONU as well as startup of ONUs with power demands in exceeding one half the source VA. System design and coordination between the RPS and ONU must prevent operation from reaching point 3. Alternatively, operation at point 3 can be avoided by using lower-power ONUs such that point 3 does not exist as seen in Fig. 5.

To avoid the unwanted, stable equilibrium at point 3 in Fig. 4, with a source limited to 100-VA, and the power loss in R_W, the maximum ONU power P_{ONU} can be related to the ONU voltage V_{ONU} as

$$P_{ONU,\max} = 100W \frac{V_{ONU}}{V_{RPS}} \qquad (1)$$

As (1) shows, for lower ONU voltages, as with longer RPS-ONU copper loops, the maximum ONU power is reduced from the 100-VA of the source. The minimum operating ONU voltage is V_{LVD}, which is one-half of the RPS open-circuit voltage V_{RPS}. Thus, if the 100-VA limit is strictly followed, the maximum ONU power at the end of long RPS-ONU copper loops is 50W.

Referring still to Fig. 4, the negative small-signal resistance of the ONU characteristics at points 1 and 2 makes any generalizations regarding their stability more difficult. Analysis of point 2 shows this as an unstable equilibrium. Point 1, which is the desired operating point is typically stable. In the microprocessor systems discussed in [2], point 2 can be an unstable point, but all practical examples with copper twisted pairs, wiring inductance L_W and resistance R_W, and ONU capacitance C_{ONU}, this is a stable equilibrium.

6. Startup Dynamics

Pspice is used to provide simulations of the dynamics of the circuit in Fig. 1. The Pspice circuit is seen in Fig. 6 where the nonlinear, constant-power ONU load, along with the LVD of the ONU, is modeled with the voltage-controlled current source, G1. For a 40-W ONU load with a 75-V LVD, the voltage-current pairs which define G1 are given by (100,0) (0,0) (75,0.01) (75.01,0.533) (85,0.471) (100,0.4) (120,0.333) (150,0.266) (200,0.2) (300,0.133) (600,0.0666). An ONU with a different load power can be simulated by

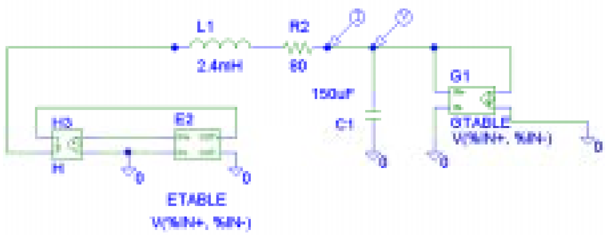

Figure 6. Pspice circuit for state plane simulations.

changing the current in each voltage-current pair which is associated with a voltage equal to or greater than 75.01V.

Inductance of the copper twisted pair connecting the RPS and ONU varies with length, wire gauge, proximity, and tightness of the twists. An approximate inductance can be computed from a nominal approximation of 10nH/inch of wire. For a 2-mile loop, the loop inductance is thus approximated as 2.5mH . Alternatively the inductance, L, is of the order

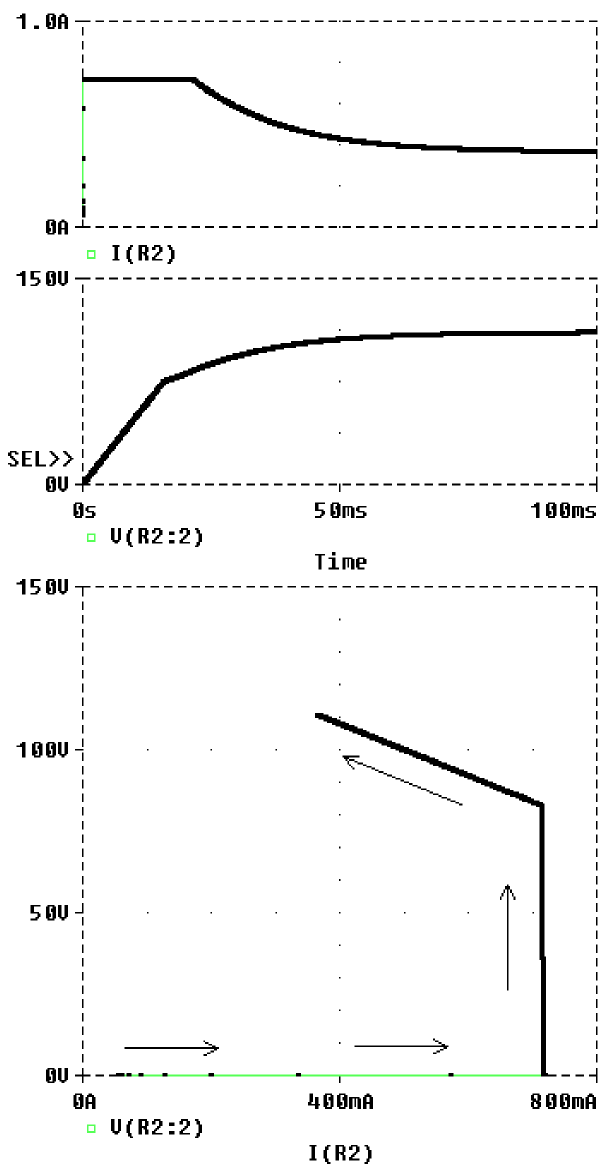

Figure 7. Startup simulation with a 40-W ONU load, R_W = 80Ω, L_W = 2.4mH, and C_{ONU} = 150µF. Lower figure is the state-space trajectory with inductor current on the horizontal axis, and capacitor voltage on the vertical axis.

1mH/mile [3]. Here, a 2.4mH value is used for L_W.

To overcome the limited selection of controlled sources supplied with the public-domain Pspice software, the current-limiting function of the RPS source is modeled with two controlled sources: E2 and H3. Using a unity-gain transconductance amplifier, current through voltage-controlled voltage source H3 is converted into a voltage which allows voltage-controlled voltage source H3 to function as a current-controlled voltage source. The input voltage (equal to current), output voltage pairs used in defining the nonlinear H3 gain are (-100,140)(0.714,140)(0.72,0).

Using initial conditions of i_{LW}=0A and $V_{C,ONU}$ = 0V, the startup dynamics are plotted on the i_{LW} and $v_{C,ONU}$ state plane in the lower portion of Fig. 7. The system in Fig. 1 is a nonlinear, second-order system, and two convenient state variables are the capacitor voltage and inductor current. The start of the turn-on trajectory occurs at the lower left-hand corner (0A, 0V) of the state plane, after which the current rises quickly to the RPS source limit during charging of C_{ONU}. Below the V_{LVD}, no current flows into the ONU load, but as V_{ONU} rises above V_{LVD}, the ONU current becomes nonzero, reducing current flow into C_{ONU} and lowering the rate of rise (slope) of V_{ONU}. Finally, steady-state operation is attained at V_{ONU}= 111.23V, and $i_{L,W}$ = 0.36A.

Contrasting with this successful 40-W startup, a 55-W ONU startup from zero initial conditions leads to steady-state operation at the undesired operating point V_{LVD}. Figure 8 contains these startup dynamics. During startup, as the ONU voltage reaches V_{LVD}, the ONU current load current is calculated as

$$I_{ONU}(V_{ONU} = 75) = \frac{P_{ONU}}{V_{LVD}} = \frac{55W}{75V} = 0.733A \qquad (2)$$

while the current-limiting of the RPS limits the maximum source current to 0.714A. Thus, the ONU voltage cannot rise above the LVD voltage of the ONU. If, however, as shown in Section 8, the ONU startup is delayed until the ONU voltage reaches its open-circuit steady-state voltage (140V), a 55-W ONU load will reach the desired steady-state operating voltage. State-space trajectories cannot cross each other [5] and thus any initial condition which lies on the trajectory of Fig. 8 follows the same trajectory, leading to the identical, unwanted operating point. Thus, recovery from a short circuit at the ONU, which has a initial condition of (0V, 0.714A), follows the trajectory of Fig. 8 too.

7. Short Circuit Recovery

No specific examples for short-circuit recovery are presented since the startup from zero initial conditions provide the information for analysis of the short-circuit startup. A short circuit can occur in any location within the RPS-ONU copper twisted pairs, although the most likely locations are at the RPS or at the ONU. Many RPS-ONU installation use a composite cable which consists of copper twisted pairs co-located with the optical fibers transmitting the optical signals between the remote terminal (RT) and the ONU. Any cut or

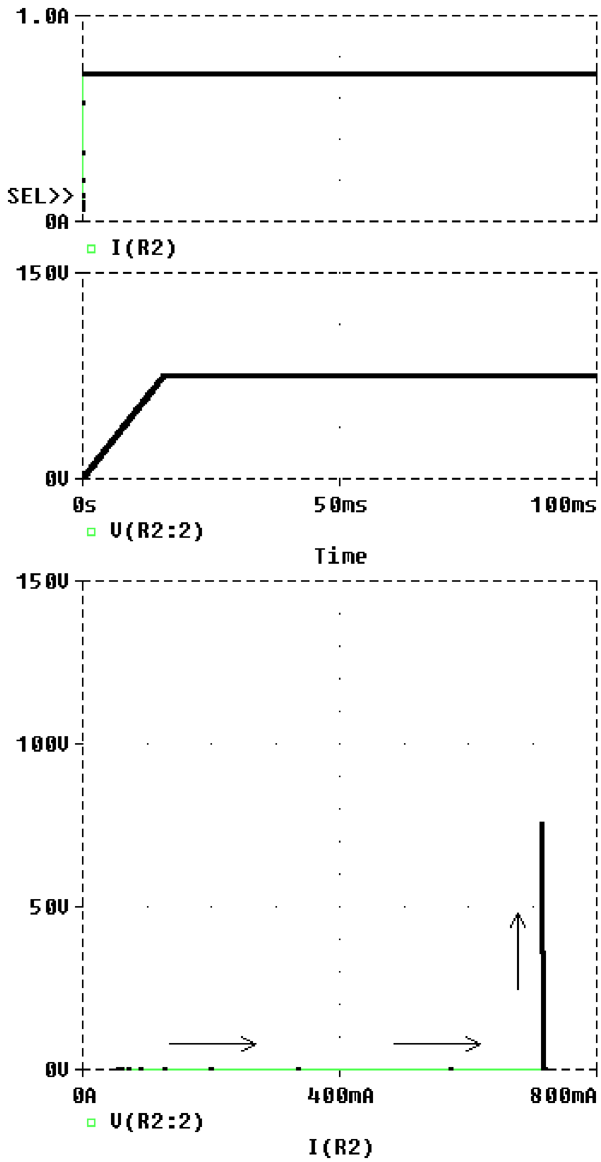

Figure 8. Startup simulation with a 55-W ONU load. Lower figure is the state-space trajectory with inductor current on the horizontal axis, and capacitor voltage on the vertical axis.

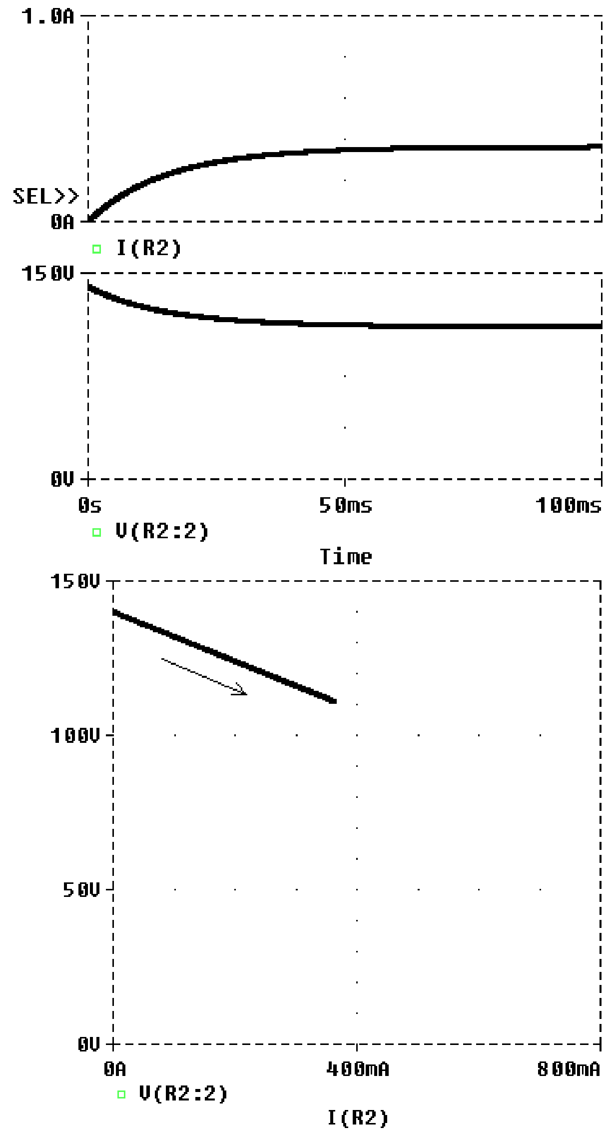

Figure 9. Delayed ONU startup with initial conditions of 140V and 0A. for a 40-W ONU load. Lower figure is the state-space trajectory with inductor current on the horizontal axis, and capacitor voltage on the vertical axis.

other intrusion likely to create a short circuit on the copper twisted pairs will also affect the fiber in the composite cable. A short circuit at the RPS end of the twisted pair produces initial condition of (0V, 0A), which is the same initial condition as the startup from zero initial conditions in Section 6. Thus, a short circuit at the RPS end of the twisted pair leads to the same trajectory as startup from zero initial conditions.

8. Delayed ONU Startup

Many ONUs are designed to delay the application of the ONU power following appearance of voltage at the ONU. With this delayed start, the ONU operating dynamics start from an initial condition of (140V, 0A). Figure 9 contains the time-domain response from this initial condition along with the state space trajectory. As Fig. 9 illustrates, the trajectory leads to the same, desired operating point as did the trajectory resulting from zero initial conditions.

As presented in Section 6, a 55-W ONU does not start up successfully from zero initial conditions. Here, the delayed start of the 55-W ONU allows the 55-W ONU to reach steady-state operation at the desired operating point seen in Fig. 10. Although the delayed ONU start allows for a successful 55-W ONU startup, this delayed start must be initiated during any transient at the ONU which brings the ONU capacitor voltage below the LVD voltage, however momentary. Thus, if ONU operation is controlled by an internal ONU microprocessor, the reset function of this microprocessor must react rapidly to any drop in ONU input voltage below V_{LDV}. Services supported out of the ONU are lost during the interval in which the ONU microprocessor is restarting the ONU, and also for the time during which the ONU must resynchronized itself with the optical data stream. This resynchronization can consume some significant time, on the order of seconds and more. But, if the removal of power ONU is not undertaken for a momentary ONU voltage below V_{LVD}, the ONU will operate in steady

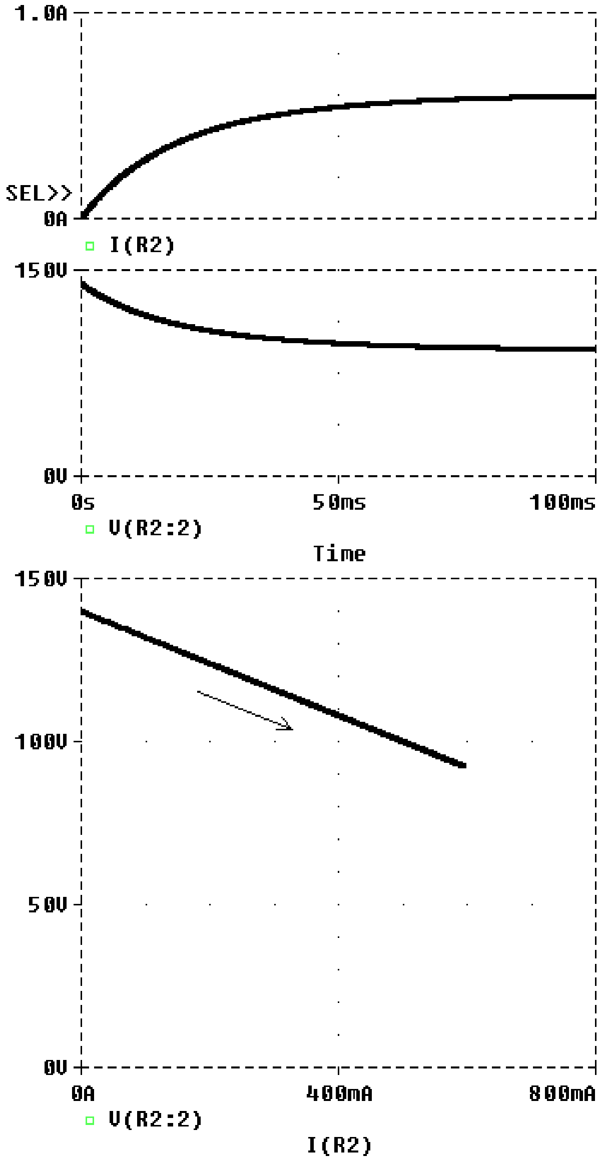

Figure 10. Delayed ONU startup with initial conditions of 140V and 0A. for a 55-W ONU load.

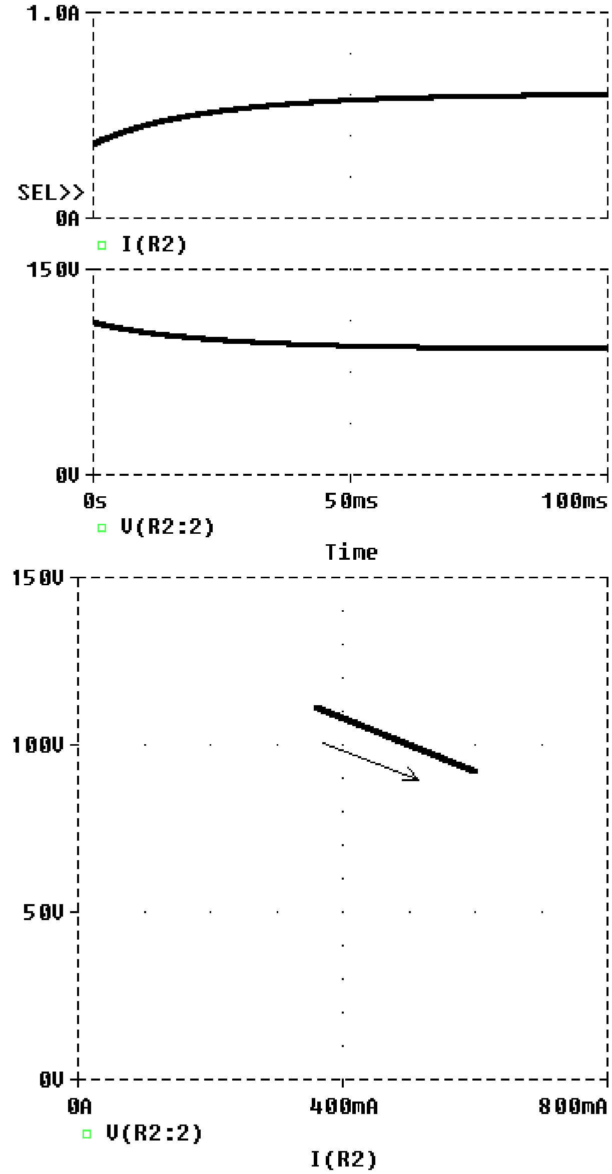

Figure 11. Step change respone for an ONU power change from 40W to 55W.

state at V_{LVD}, and never recovery to its normal operating voltage.

9. General ONU Step Load Response

The power load at the ONU can vary as different services offered out of the ONU create varying power loads. Here, we examine the transient response of a change in ONU powering load from 40W to 55W. Figure 11 contains the time-domain characteristics along with the state plane plot. This step response is unremarkable and shows that an ONU step change in power from 40W to 55W with the component values of Fig. 6 leads to a desired, stable operating point.

For the same step change in power, 40W to 55W, the response can be significantly different when the twisted pair inductance L_W is dramatically increased. A similar effect can be produced with a smaller ONU capacitance C_{ONU}. To show the changed system dynamics, the same step change in ONU load is used with a larger twisted-pair inductance L_W of 1.3H to produce the system dynamics seen in Fig. 12. As these show, the system dynamics mark the start of a damped sinusoidal oscillation which sufficiently large to cause the ONU voltage to fall below V_{LVD} which then leads to operation at the undesired operating point characterized by an ONU voltage equal to V_{LVD}.

10. Conclusions

Long RPS-ONU loops produce lower ONU voltages V_{ONU} which can lead to operation at an undesired operating point characterized by an ONU voltage of V_{LVD}, and a loop current equal to the current limit of the RPS source. Although such operation is not likely to be present in normal RPS-ONU deployments, careful analysis is always necessary to ensure reliable, robust operation, especially among all operating conditions.

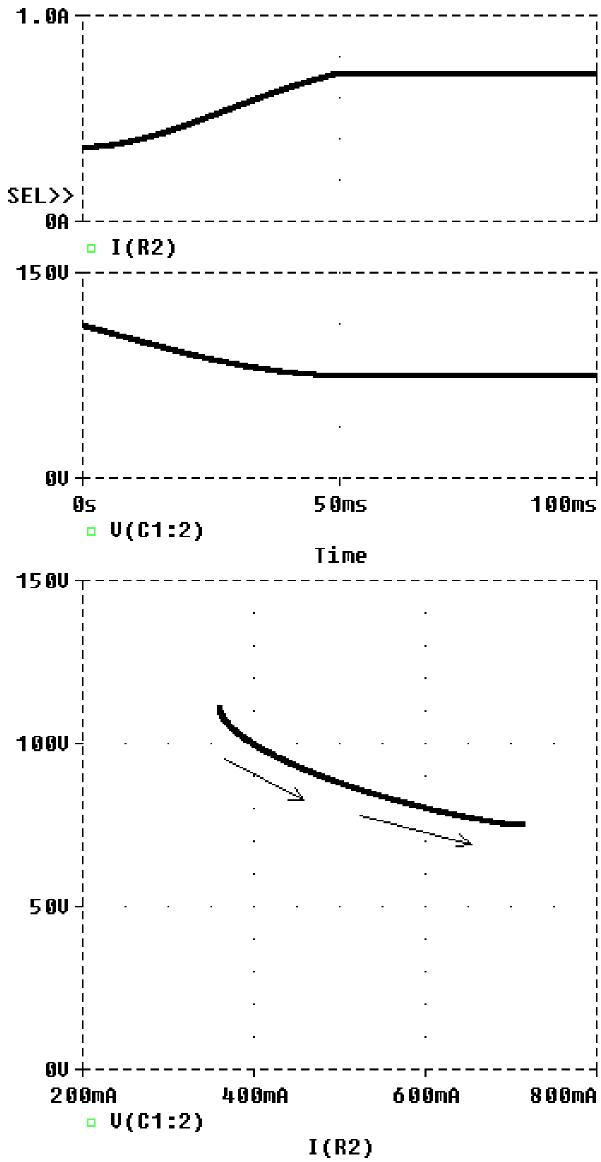

Figure 12. Transient response to step chane in ONU load from 40W to 55W with a larger twisted-pair inductance L_W = 1.3H.

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