Extending SWER Line Capacity

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***Abstract*—SWER lines, with increasing load demand over time, begin to experience voltage sags during peak periods most often in little over half their asset life. Voltage sags are due most often to the lossy nature of SWER networks, and in lines over 100km, there is reserve thermal capacity to allow for use of LV customer voltage regulators. This paper provides methodologies as to how far toward the theoretical maximum power transfer point this can occur, as well as design considerations for the LV voltage regulators.**

Keywords— SWER line, voltage regulators

I. Introduction

Traditionally Single Wire Earth Return (SWER) lines operate for sparse rural customer electricity networks with a supply voltage variation of ±6% or ±10%. In Australia, they vary from less than 70km length in Victoria to over 400kms in Western Queensland. Ergon Energy operates its 65,000 km SWER networks at 11kV, 12.7kV or 19.1kV in many configurations including isolated, un-isolated, duplexed and triplexed wire systems; with a total connected customer transformer capacity of 253MVA (Ergon Energy 2011). Chapman [1], and Ergon Energy [2] report typical Queensland SWER line characteristics as 0.3 - 0.5kVA loading per km and average maximum customer demand of 3.5kVA. Individual maximum loads are between 2kW to 15 kW, including a few special loads requiring a 100kVA step down transformer. Line lengths between customers are 1km up to 20km, with a few isolated rural properties being up to 25km or more apart. SWER supply networks typically have a capacity of between 100 - 200 kW. In the past 35 years, rural load demand for Queensland SWER lines has increased due to increasing agricultural irrigation needs, post-harvest washing / packing preparation (often with refrigeration units), and farm automation loads. Earlier SWER customer distribution transformers are being upgraded from 3.5kVA to 10kVA, or 12kVA and even 25kVA. Such compounding load demand has resulted in peak load period voltage sag problems on many rural networks. Peak loads are being compounded in rural regions agricultural sectors having reduced diversity factors as a result of similar peak load concurrence.

Researching the Australian Bureau of Statistics (ABS) 2010 report, "End use energy intensity in the Australian Economy" [3] reveals that the energy use / growth rate for rural areas. In this 2010 report, the ABS figures for rural and remote agriculture Australia-wide energy usage had been increasing at an average rate of 2.1% per annum for the period 1989/90 to 2007/08. This is significantly higher per rural customer than the ABS reported inner and outer agricultural regions population of 0.3% and 0.4% per annum respectively. By comparison city and town residential energy use increased 1.63% per annum compounding for the period 1989/90 to 2007/08. [3] Total electricity demand growth for agricultural use plus rural residential use, though of different base units, will aggregate to give a total between nominal range of 2.1% to greater than 3.0% growth per annum for rural energy supply utilities. Nobbs [4], Hoseinzadeh and Rattray [5] report Ergon Energy's SWER network in Queensland as ranging in age between 25 – 45 years, and having regular voltage sags. Nobbs [4] also reports that review by Ergon Energy in 2010 revealed 14% of SWER networks experienced thermal overloads in the supply, with a further 6% approaching full capacity. At that time, 18% of Ergon Energy's SWER networks were operating with regular supply voltage sags with a further 5% regularly nearing voltage limits.

The maximum Australian SWER networks asset life most often depends on the life of the species of hardwood pole whose replacement life is 55 – 80 years [6]. The other potential limiting life factor of Australian SWER lines is the Steel (SC/GZ) conductor. The low capital cost SC / GZ steel galvanised SWER line conductor used in many Australian rural SWER lines, has a limited life expectancy in a high moisture and salt laden corrosive environment (for example the Gippsland region of Eastern Victoria). In such environs, the galvanised steel conductor has a 65 – 70 years usable life, before the zinc coating is reduced to have insignificant protective effects [7]. In ex-colonial developing nations, where steel poles or steel edge braced concrete poles are used, here SWER line asset life can easily extend to over a hundred years. This paper explores issues thermal line capacity and maximum power transfer capacity potential, particularly in the face that Australian SWER lines actually have a significant asset life reserve. As a benchmark, the cheapest SWER line backbone or secondary trunk line size conductor / supply asset upgrade costs generally are $18,000 per km or more, as based on the Victorian Black Friday Royal Commission report and specialist submissions to that commission[8] [9]. Such costs for sparse SWER line network customer base demographics are often prohibitive to achieve investment payback. For a SWER line of greater than 200 km long, just upgrading a 40km backbone section of line (for maybe improvement of 20 customers' voltage regulation during peak periods) requires a prohibitive capital investment of $720,000 or more. Recovering this investment from a sparse customer base through electricity charges is difficult. As a result of such potential future investment requirements, Ergon Energy is encouraging demand control in customers by changing many tariff structures to include a significant network supply service cost component and a demand component being added to the standard energy use costs. [10] [11]. However, this will drive costs of electricity up rapidly and potentially inequitably in rural power supply networks. From the legacy of existing infrastructure, SWER networks line characteristics are particularly "lossy" compared to near-infinite bus supplies used for metropolitan and industrial users. There is a great need to develop intervention strategies to ensure Australia's rural sector's access to electrical energy remains competitive, particularly to other developed economies. As a comparison, the USA and Canada have access to cheaper power, while the European Union costs are currently equal to Australia's energy costs based on international PPP (Purchasing Power Parity) [12]. But Australia's energy costs are anticipated to rise 50% above those of the EU's in the next 5 years [12]. This paper investigates:

- What is the maximum load capacity of a SWER line in relation to length of network, thermal conductor capacity and voltage collapse?
- Is this maximum capacity of the line being utilized with the usual voltage guarantee of 0.9 or 0.94 p.u. voltage?
- How to use any spare line capacity with LV Customer voltage regulator?
- How to determine the maximum "boost" range for the optimal design of a voltage regulator?
- Where thermal limit or static voltage stability is the restraining limit, how to determine the margin needed for transient starting, and how this affects the optimal boost range of a customer LV regulator?
- What is the response envelope for LV voltage regulators and surge capacity for transient load starting?

II. Modelling SWER Line Voltage Collapse

Use of LV voltage regulators effectively makes the customer loads appear to be constant power types. Introducing such regulators provides the challenge to find the theoretical load transfer limits of various SWER line conductors, and whether spare capacity for power transfer to customers exists in the conductor thermal limit or static voltage stability limit. It is noted that use of customer LV voltage regulators does incrementally increase the load on the HV line during any boost regulation operation. This can cascade further where several LV customer regulators interfere badly with each during an upstream and downstream response to another customer's voltage regulator countering a significant local step or transient load. Such potentially bad oscillatory interference between such voltage regulators can push the network into voltage collapse point if any resulting voltage swings are undamped. However, changing the SWER network to a current based power source, instead of a set limit of ±10% or ±6% of 1 p.u. voltage regulated power supply, would provide additional supply dispatch capacity to significantly extend a SWER asset's useful life.

For simplicity, theoretical SWER lines without spurs, of total lengths of 72km (that is, similar to Victorian SWER line maximum lengths), 152km, 300km and 400 (that is, similar in length to the maximum length SWER lines in Queensland) were investigated. For each of these SWER case studies, the customer nodes were equally distributed along the line length, and all customers were assumed to have the same peak load demands. These SWER lines were further optioned with two alternative conductor types. To simulate extended voltage supply regulation support over time, multiple load flows were run with increasing peak loads based on the 2.5% and 3.5% per annum compounding demand increase, until voltage collapse point was reached. A MATLAB Y-impedance matrix study was implemented with the Newton-Raphson Jacobian power flow solutions. *(Note: copies of the relevant MATLAB scripts are available by contacting the authors.)* The load flow solution outputs were the network supply node p.u. values, total power provided by the network (that is losses of the network and customer load supplied) and the Jacobian Matrix file. The results revealed a there is a significant margin between the voltage collapse point and to thermal limit that is both dependent on SWER network length, and maximum load transfer limit before voltage collapse. Referring to figure 1, here the SWER maximum power flow results (just before voltage collapse), were plotted and trended by the dashed line shown, for the four different SWER network lengths. Similarly for each total SWER line length, the entire customer nodal voltage profiles were also plotted. Figure 1 shows the trend for the 2/2.75 SC/GZ lighter conductor. It is noted that when networks are longer than 100km, the lossy nature of the SWER network reduces maximum power transfer near voltage collapse at a nominal 0.45 p.u. to be well below thermal capacity of 320kVA for the SC/GZ light conductor. *This indicates, upgrading significant portions of SWER to heavier conductor could often be a waste of investment.* This solution process was also implemented for the heavier 3/4/2.5 ACSR / GZ conductor. Figure 2 summarizes the comparative difference between the lighter and heavier conductor in their load transfer capacity versus network length.

This figure trends the thermal capacity of each line, the maximum load transfer just before voltage collapse (or static voltage regulation limit), as well as the 0.94p.u. voltage regulation load transfer limit versus the SWER network length

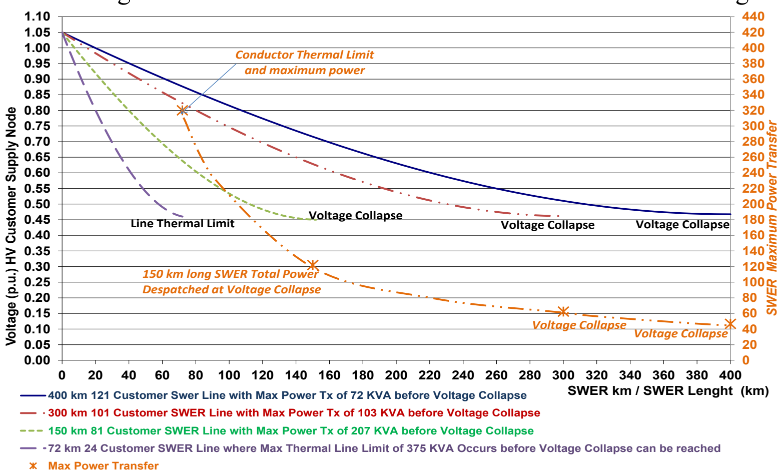

Figure 1: 3/2.75 SC/GZ conductor SWER network voltage / maximum power transfer at voltage collapse point versus SWER line length.

for each conductor. It is evident there significant reserve between thermal limit and maximum power flow before voltage collapse. Similarly there is a significant margin of unused maximum power transfer capacity compared to the 0.94 p.u. line voltage regulation limit trend. This demonstrates the reserve capacity available potentially for use with LV customer voltage regulators.

III. Modelling Results

The Newton-Raphson Jacobian block matrix equation 1 for this solution is written as:

$$\begin{bmatrix} \triangle P \\ \triangle Q \end{bmatrix} = \underbrace{\begin{bmatrix} \text{Jaco1,1} & \text{Jaco1,2 i.e. } {}^{\triangle P}/_{\triangle V} \\ \text{Jaco2,1} & \text{Jaco2,2 i.e. } {}^{\triangle Q}/_{\triangle V} \end{bmatrix}}_{\text{Jacobian}} \cdot \begin{bmatrix} \triangle \delta \\ \triangle V \end{bmatrix} \quad (1)$$

Here the Jacobian matrix has been divided into four sub-matrices, and these have been labeled $Jaco_{1,1}$ for the upper left hand sub-matrix, $Jaco_{1,2}$ for the upper right sub-matrix, and similarly for the bottom two sub-matrices, as $Jaco_{2,1}$ and $Jaco_{2,2}$. Of interest in this study was the main diagonal elements of systems $Jaco_{1,2}$ representing ${}^{\Delta P}/_{\Delta V}$ and $Jaco_{2,2}$ representing ${}^{\Delta Q}/_{\Delta V}$ elements. Here a review of the customer node sensitivity to voltage sag on the SWER line as it faced increasing load demand was examined to see if these could indicate voltage collapse was imminent. When maximum power transfer point for any of these given SWER networks was being approached, then small changes in load at the customer with the worst voltage droop, (which in this simplified case is the last customer), begin to produce disproportionately large incremental drops in voltage. This was found to be reflected particularly in the $Jaco_{1,2}$ sub-matrix diagonal element corresponding to the worst customer.

A. Margin for Customer LV Voltage Regulators

Examination of the power flow solutions' revealed how to recognize approaching voltage collapse using the relevant customer sub-matrix $Jaco_{2,1}$ element and when it rapidly reduces towards zero. Figures 3 - 9 show this knee-over trend starting when the customer node approaches 0.65 p.u. voltage. This trend was confirmed for all four line lengths studied, not just the two illustrated in this paper (that is the shortest and longest line case). This $Jaco_{2,1}$ (or ${}^{\Delta P}/_{\Delta V}$ factor) trend in response to compounding increasing loads of 2.5% or 3.5% per annum compounding, is particularly evident in figures 5 and 9. (Note: As the 72km 3/2.75 SC/GZ conductor was already at thermal limit just before voltage collapse, the worst customer's $Jaco_{12}$ element plot was not included or shown.) For both conductor types, figures 3, 4, 6, and 8 also show the period in which voltage guarantee to 0.94 p.u. can be achieved unaided, and the subsequent potential year period when LV customer series voltage regulators (such the Micro-Planet® voltage regulators used by ERGON ENERGY [10]) could be utilized to provide local customer voltage support. These curves also

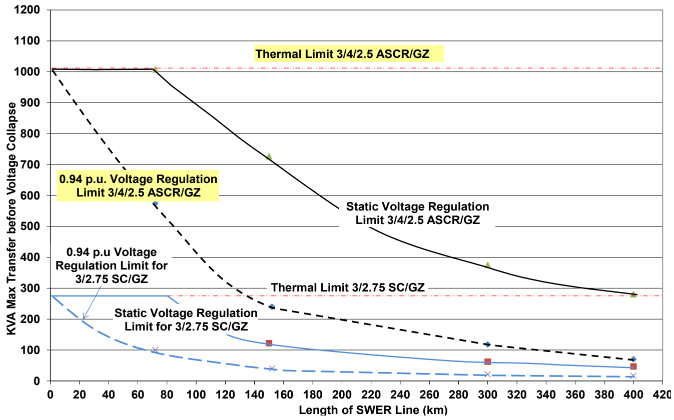

Figure 2: 3/2.75 SC/GZ (thin) and 3/4/2.5 ASCR GZ (thicker) SWER conductor comparison of maximum current thermal limits.

give indication at 0.65 p.u. HV voltage sag, of the nominal margin in capacity maximum power transfer point, which potentially could be used to provide for transient load stability. This research example provides a basic methodology to identify the load capacity margin, and likely period of operation in years that voltage regulators could be utilized to counter HV voltage sags during SWER peak demand periods. For individual actual SWER networks, sectional line load and economic analysis would naturally follow to better detail how many LV customer voltage regulators could be utilized, as compared to specific line section conductor upgrade alone, or in combination with such customer voltage regulators. But, LV customer voltage regulators have the potential to provide another one, two to even three decades of extension of the usable life of the SWER asset. It should be noted, as for example, if the line HV voltage is permitted to drop to 0.65p.u., then the local customer node with a voltage regulator will draw an additional 29% of HV line current to boost the load side voltage to 0.94 p.u.. For this example, if a MicroPlanet® [10] units or like are used, this results from the LV voltage regulator requiring additional current through a boost circuit of its toroidal transformer. This transformer has an additional take off point on the non-load side of the LV supply, with a boost inverter for increasing voltage output via the transformers secondary winding to within ranges of ±10%, ±6% or even less than 1% of the nominal LV set reference supply voltage. SWER lines of length over 100km, there is a range of reserve power capacity in the line, or network branches, even in the thinner galvanised steel 3/2.75 SC/GZ type SWER conductor, for voltage regulators support at the customer LV supply.

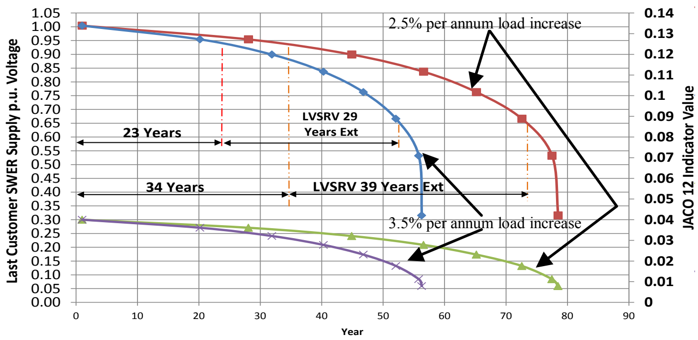

Figure 3: Last customer voltage / *Jaco(2,1)* diagonal factor trends vs. typical rural load annual incremental increases for 72km 46 customer 3/2.75 SC/GZ light SWER conductor.

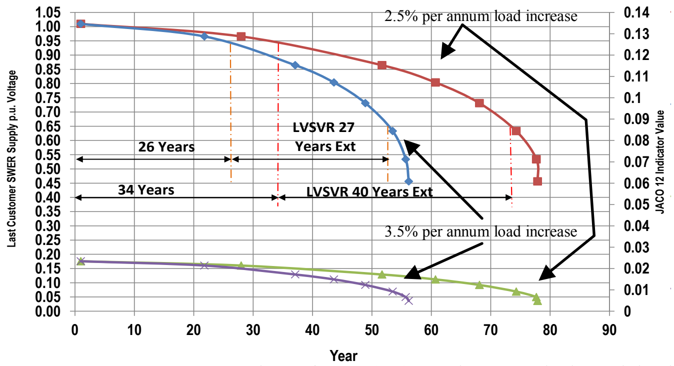

Figure 4: Last customer voltage / *Jaco(2,1)* trends vs. typical rural load annual incremental increases for 400km 120 customer 3/2.75 SC/GZ thinnest SWER conductor.

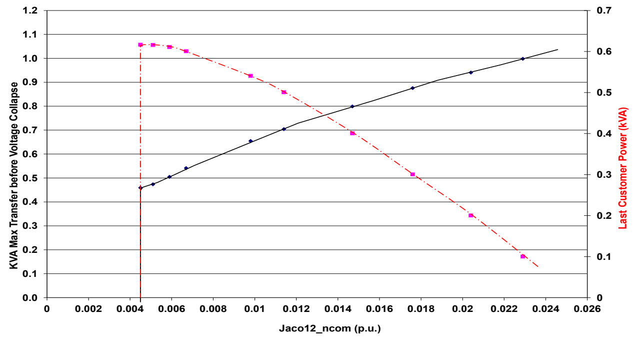

Figure 5: Corresponding to Fig 4 for 400 km SWER illustrating ΔP/ΔV trend for 3/2.75 SC/GZ light SWER conductor reaches maximum power transfer, where a small increase in load produces disproportionate voltage sag; and Jaco(2,1) matrix quadrant main diagonal value has approached its smallest value of 0.044.

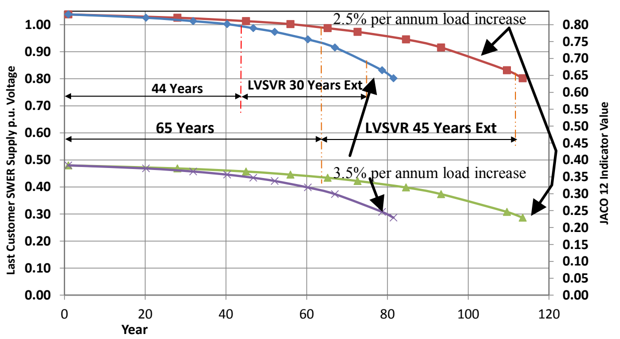

Figure 6: Last customer voltage / *Jaco(2,1)* matrix quadrant diagonal value trends vs. typical rural load annual incremental increases for 72km 61 customer 3/4/2.5 ACSR / GZ heavier SWER conductor.

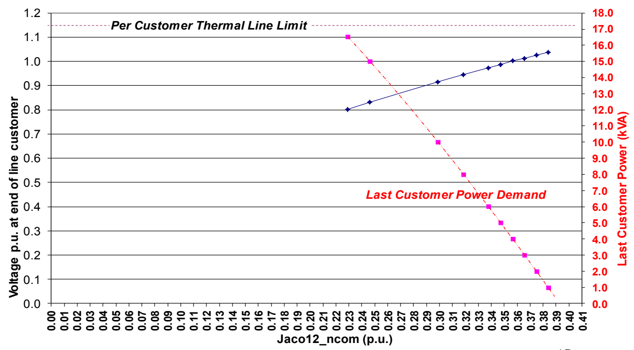

Figure 7: Corresponding to Fig 6 for 70 km SWER illustrating $^{\Delta P}/_{\Delta V}$ trend. Note in this case use of the heavier SWER conductor, even on the shortest line, voltage collapse occurs prior to reaching the line's thermal limit.

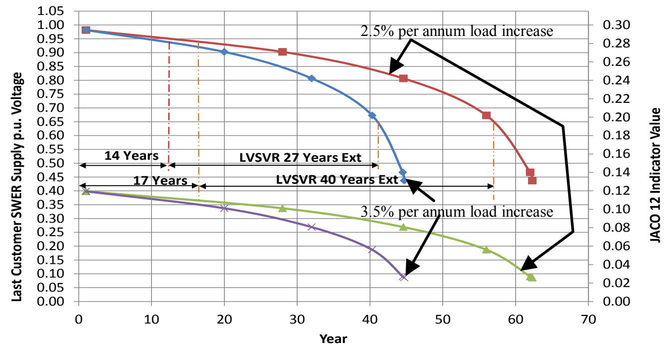

Figure 8: Last customer voltage / *Jaco(2,1)* matrix quadrant diagonal value trends vs. typical rural load annual incremental increases for 400km 120 customer 3/4/2.5 ACSR / GZ heavier SWER conductor.

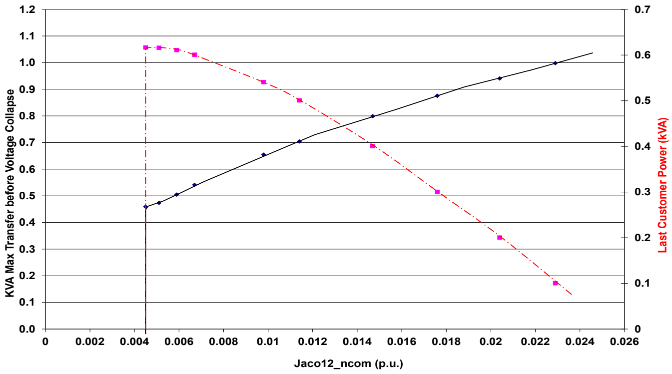

Figure 9: Corresponding to Fig 8 for 400 km heavier SWER conductor illustrating $^{\Delta P}/_{\Delta V}$ trend reaches maximum power transfer Jaco(2,1) matrix quadrant main diagonal value has approached its smallest value of 0.046 and then drops rapidly towards zero.

LV Voltage regulators are good for the customer, but do increase the burden on the SWER HV network. The more customer voltage regulators needed on a SWER line for local voltage control, incrementally in time with rising demand, this forces the SWER line to more rapidly approach maximum power / voltage collapse. ***The question remains as to how far it is safe to use this margin to extend local customer voltage regulation, while allowing the HV network to sag towards the maximum power transfer point?***

B. Determining SWER Line Maximum Power Transfer

For the same network case results for these simple single line SWER networks, the steady state voltage stability limit can also be plotted. This also demonstrates the maximum power transfer point. Figures 10 – 13 show the corresponding power transfer curves developed from the uniform loading. These are based on the same load flow nodal load inputs to the network, and their Jacobian solutions recorded in figures 3, 4, 6 and 8. For these single line networks, total network power dispatch (that is network losses plus customer loads) does directly correlate to this same voltage stability limit, and to individual customers load by factor equal to the number of customers on the network. However, for SWER networks, and especially for more complex branching types, the maximum voltage stability limit will be defined by the heaviest local load possible at the customer with the worst voltage sag.

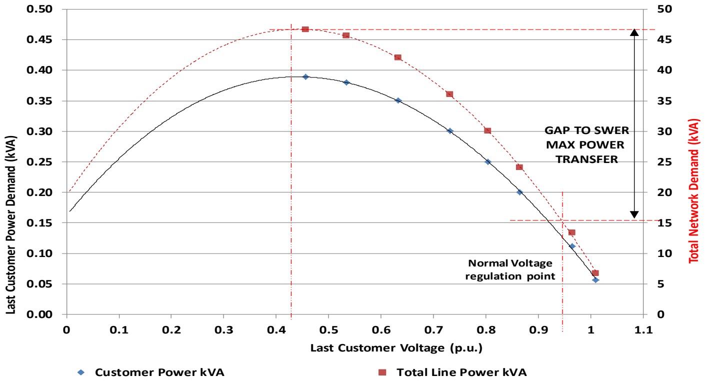

Figure 10: Power transfer plot and trendline determination of maximum power transfer at last (and worst) customer or network voltage sag node for single line 400km 121 customer 3/2.75 SC/GZ light SWER conductor.

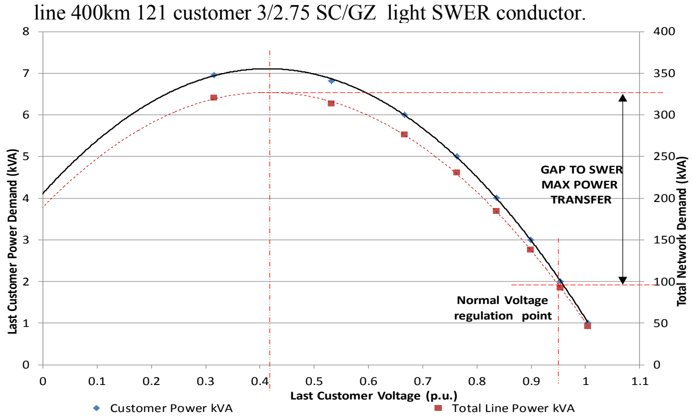

Figure 11: Power transfer plot and trendline determination of maximum power transfer at last (and worst) customer or network voltage sag node for single line 72km 46 customer 3/2.75 SC/GZ light SWER conductor.

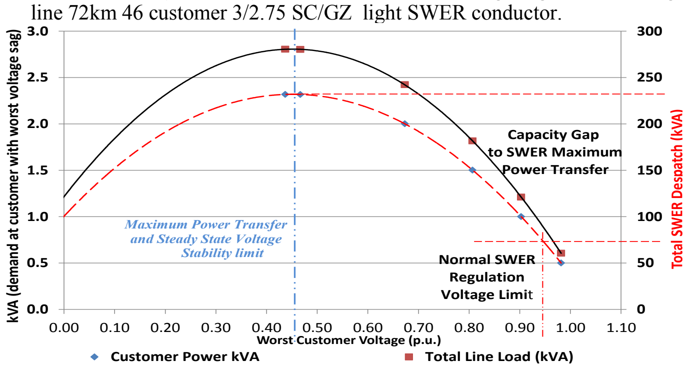

Figure 12: Power transfer plot and trendline determination of maximum power transfer at last (and worst) customer or network voltage sag node for single line 72km 46 customer 3/4/2.5 ACSR/GZ SWER conductor.

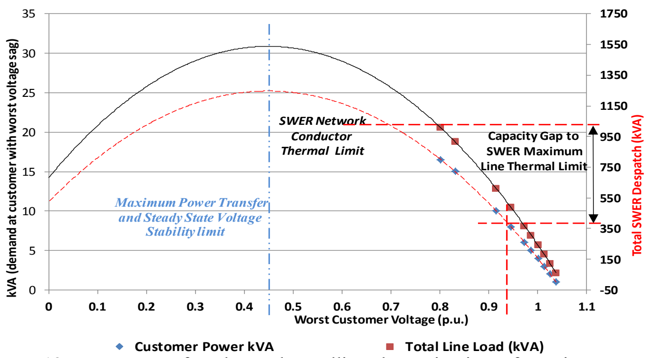

Figure 13: Power transfer plot and trendline determination of maximum power transfer at last (and worst) customer or network voltage sag node for single line 400km 121 customer 3/4/2.5 ACSR/GZ SWER conductor. *Note the conductor thermal limit occurs before maximum power transfer.*

This also corresponds to the rapid decline towards zero of the $Jaco_{2,1}$ sub-matrix diagonal value that corresponds to this worst customer node, as per the examples already shown in figures 5 and 9.

C. *HV Voltage Sag Limits for LV Regulator Design*

Reviewing the MicroPlanet® low voltage regulators currently being installed on ERGON ENERGY problem SWER customer supplies [11], shows their current regulation ability is a conservative ±16% about the nominal line voltage. These voltage regulators as they face the continuing rises in annual rural power demand in the range of 2.5 – 3.5% per annum will potentially not provide the maximum longevity of additional regulation period. These static voltage collapse studies indicate that a supply side network line could potentially be run down to 0.65p.u. voltage. This SWER analysis potentially suggests that a wider range of regulation is require, possibly up to +35% regulation boost and -16% buck may be more appropriate. However, the question then remains how to maintain some stability margin away from the static voltage regulation point for any additional transient load, for example a motor start without potentially causing voltage collapse? Determining the maximum design boost range for a LV voltage regulation for any specific SWER line could adopt the proposed following. As an example referring to figure 14, take the 72km 46 customer SWER line with 3.5% per annum rising and compounding load demand and using a worst case dynamic starting load. In this case, a margin of 66kVA should remain for a large single phase 7.5kVA motor DOL start. This is based on a motor start at the worst customer node having locked rotor currents of up to 800% for two pole and 590% for a four pole motor [12] on the load side of a customer voltage regulator. Figure 14 also illustrates how to determine the needed maximum range of voltage regulation of nominally allowable +30% boost to maximize the voltage regulation extension period to 25 years. This would provide another decade of voltage regulation compared to the MicroPlanet® unit's regulation range of 16%, which would provide for a maximum of 15 years regulation. It is further noted, the LV customer voltage regulator also has the requirement to be able to handle a maximum surge rating of 66kVA single phase motor start surge capacity for a period up to 10 seconds. But as noted from figure 1 line node voltage trends, not all customers on such a network, would require this maximum boost range.

IV. CONCLUSION

Applying this demonstrated methodology to any SWER line, allows additional load transfer capacity towards an acceptable point of maximum load transfer with a safe stability capacity margin for transient loads to prevent voltage collapse. Note: Allowance for transient capacity margin away from maximum power transfer point, is to be based on anticipated maximum starting loads, but including any needed diversity factor for any multiple concurrent such load starting. Understanding all of this, allows for more optimal design of LV customer voltage regulators. Surge capacity for such voltage regulators would also have to be

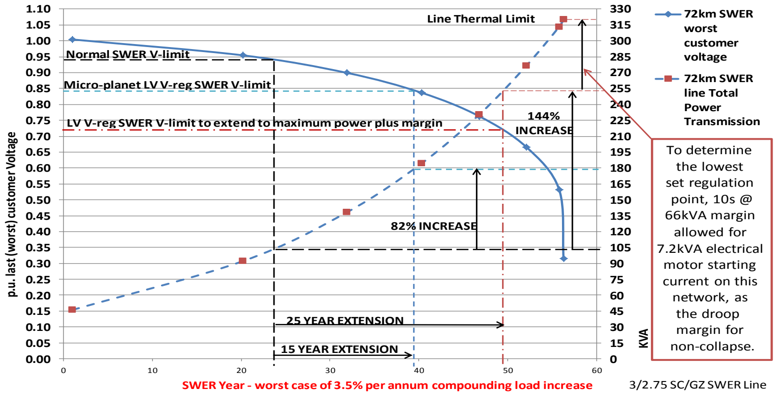

Figure 14: Determining the voltage regulator range for 72km 3.4.2.5 ACSR/GZ SWER Example

compliant to transient start conditions to IEEE 1100 standard safe working area for voltage transients as shown in figure 15. Here, between the times of 0.5 to 10 seconds, the normal period for motor starting, up to an 18% temporary voltage dip is permitted for such devices so as not to damage other electronic or domestic electrical equipment in a rural residence on the same supply. This raises stability issues to be further explored. The IEEE envelope (figure 14) for voltage transient to safe load operation responses raises the questions about response time to voltage changes (for example due to boost effects of LV voltage regulators) and define how to distinguish between a load step and a transient motor starting step? Traditionally HV network series voltage autotransformer regulators have had to have delay times introduced to prevent over-reaction to transients, whereas traditionally LV electronic regulators react very quickly, perhaps too quickly where multiple upstream or downstream customer regulators react from a local customer load change being compensated for by such a device. Research is in progress to determine the control algorithm of a LV series voltage regulators response to prevent them badly interfering with each other, and destabilizing the HV line voltage during transient disturbances, load swings or protection operations.

There are areas of other continuing research. Electronic boost / buck LV customer voltage regulators, like the MicroPlanet® types currently being installed, with their electronic switches in circuit at most times are likely to have a nominal cycle asset life of only 10 years. A longer life switched boost buck LV voltage regulator is required with wider range boost design that matches the 2 plus decade potential use indicated by this research. Similarly, there is continuing research with the use the Jacobian $Jaco_{2,1}$ sub-matrix diagonal values and the inverse Jacobian matrix solution to better understand and use the embedded information for response strategies.

Concluding, this research indicates there is significant scope in SWER capacity for networks >100km in length to increase SWER line capacity by increasing HV supply voltage droop towards the maximum power transfer point by use of LV customer based voltage regulators. The examples provided, shed light on potential methods to define this, as well as the range of boost required, margin for transient load starting and surge capacity for LV regulators to extensively extend the

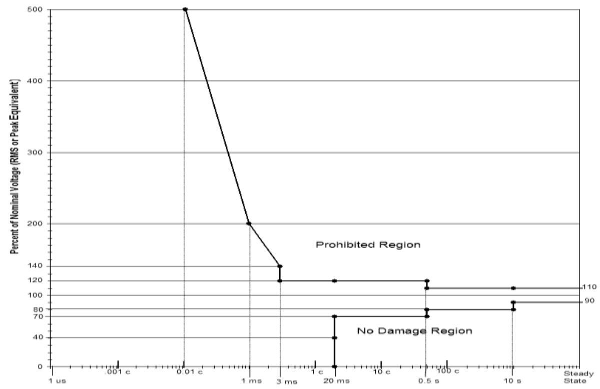

Figure 15: IEEE Std 1100-2005 IEEE Recommended Practice for Powering and Grounding Electronic Equipment – new standards Figure 3:10.

power transfer capacity of SWER lines beyond traditionally used HV supply voltage limits. The methodologies demonstrated here can be used and extended (by use of more extensive Y-impedance matrix) to model actual real SWER networks. ***Extending SWER capacity at minimal cost by such methods is particularly of important to developing nations' regional agricultural enterprise development, as well as Australian rural power users facing rapidly rising energy, zoned supply cost charges and new maximum demand costs.***

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