Assessment Of Voltage Stability And Power Quality Of Selected Medium-Voltage Distribution Feeders In The Tanesco Arusha Region, Tanzania,

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***Abstract*—Long, radially operated medium-voltage feeders are a defining feature of electricity distribution in northern Tanzania, where dispersed rural loads must be served over considerable distances and under a highland tropical climate. This paper assesses the steady-state voltage stability and power quality of eight primary 33 kV and 11 kV feeders of the Tanzania Electric Supply Company Limited (TANESCO) Arusha Region, and unlike a conventional isothermal study explicitly incorporates the prevailing weather conditions of the study area. Using the tabulated physical parameters of each feeder together with Arusha climate normals, a uniformly distributed-load model is combined with a temperature-dependent conductor resistance and an IEEE Std 738 steady-state thermal rating to estimate the full-load current, series impedance, voltage regulation, real-power loss, ampacity, power angle and the Fast Voltage Stability Index (FVSI) of every feeder under both design and hot-weather conditions. Voltage regulation is found to correlate almost linearly with feeder load moment (r = 0.97); the Monduli, Usa River (KIA) and M3 feeders are critically stressed, each with FVSI above unity and regulation far beyond the ±6% statutory limit. Elevated conductor temperature on a hot, still, sunny day is shown to raise losses and voltage drop by up to 18% and to lower the 100 mm² ampacity to about 281 A, below the M3 feeder load, converting a marginal thermal condition into a genuine overload. The two rainy seasons additionally expose the overhead network to lightning- and storm-related interruptions. Weather-aware mitigation is recommended and prioritised.**

Index Terms*—*Ampacity, distribution feeders, Fast Voltage Stability Index, IEEE 738, power quality, TANESCO, voltage regulation, weather conditions.

I. INTRODUCTION

Reliable and good quality electricity supply depends not only on adequate generation but also on the ability of the distribution network to deliver power to the point of use within acceptable voltage and stability limits. In the United Republic of Tanzania, the distribution system operated by the Tanzania Electric Supply Company Limited (TANESCO) is characterized by extensive medium voltage (MV) feeders that traverse sparsely populated districts (Gönen, 2014; Kersting, 2018). Such feeders combine large electrical distance with modest conductor cross sections, a combination that tends to produce excessive voltage drop, high resistive loss and, in the limit, voltage instability at the remote extremities of the network (Kundur, 1994; Kundur et al., 2004; Taylor, 1994; Van Cutsem & Vournas, 1998; Van Cutsem, 2000).

The performance of an overhead feeder is not independent of the weather. Ambient temperature and solar radiation raise the operating temperature of the conductors, increasing their electrical resistance and therefore the voltage drop and loss, while simultaneously reducing the current the conductors can carry before their thermal limit is reached. Wind speed governs convective cooling and hence the thermal rating, and rainfall, lightning and storms concentrated in distinct wet seasons are the principal causes of momentary interruptions and voltage sags on exposed rural lines. A power quality and stability assessment that ignores these climatic factors therefore risks being optimistic.

This paper examines eight feeders of the TANESCO Arusha Region. In the absence of continuous power-quality instrumentation on every feeder, an analytical screening approach is adopted in which the physical and loading parameters of each feeder, together with the climate normals of Arusha, are used to estimate its voltage regulation, loss, thermal utilization and voltage stability margin under both design and hot-weather conditions. The objective is to rank the feeders by severity, to identify those that violate statutory limits, to quantify the additional stress imposed by the local climate, and to recommend targeted, weather aware reinforcement. Section II describes the network, Section III the weather and climatic conditions, Section IV the methodology and governing equations, Section V the results and discussion, Section VI the mitigation measures and Section VII the conclusions.

II. THE TANESCO ARUSHA REGIONAL NETWORK

The eight feeders studied are supplied from grid-injection substations that step the TANESCO 220/132 kV transmission voltage down to 33 kV and 11 kV. Four feeders operate at 33 kV (Longido, Monduli, Usa River from KIA and Usa River from Mount Meru) and four at 11 kV (M1, M2, M3 and Corona). A conceptual single-line representation of the region is shown in Fig. 1. Each feeder is radial and carries a number of pole-mounted distribution transformers distributed along its route.

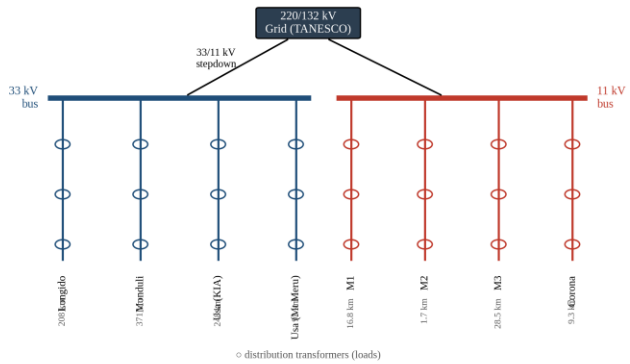

Fig. 1. Conceptual single-line diagram of the eight studied TANESCO Arusha feeders, grouped by nominal voltage.

The physical parameters of the feeders, compiled from TANESCO field records, are summarized in Table I. The overhead conductors are aluminium, predominantly of 100 mm² cross-section, with the urban M1 feeder using 50 mm². The recorded route length of the Longido feeder (originally tabulated as 2 076 km) is inconsistent with the geography of the Arusha–Longido–Loliondo corridor and is treated here as a data entry artefact corrected to 207.6 km, as noted in Table I. The tabulated length is taken to represent the total conductor route length of each feeder.

Table I: Physical Parameters of the Studied Feeders

Feeder	Length (km)	Conductor (mm²)	No. of TX	Max. demand (MW)	Voltage (kV)	Coverage area
Longido	207.6	100	500	1.9	33	Arusha, Longido, Loliondo
Monduli	370.8	100	120	7.0	33	Monduli
M1	16.8	50	94	2.0	11	Arusha Town
M2	1.7	100	108	1.0	11	Arusha Town
M3	28.4	100	230	5.0	11	Arusha Town
Usa River (KIA)	248.4	100	408	10.0	33	Usa River
Usa River (Mt Meru)	92.7	100	218	2.0	33	Arusha Town
Corona	9.3	100	58	0.5	11	Arusha Town

Note: The Longido feeder length is corrected from an anomalous tabulated value of 2 076 km to 207.6 km. TX = distribution transformers.

III. WEATHER AND CLIMATIC CONDITIONS OF THE STUDY AREA

Arusha lies on the southern slopes of Mount Meru at an elevation of about 1 350 m, which gives it a temperate highland tropical climate (Köppen class Cwb). Mean daily maximum temperatures are moderate, ranging from about 26 °C in the cool months of June and July to about 30 °C in February, while night-time minima fall to 14–16 °C. Rainfall follows a bimodal pattern: an intense "long-rains" season from March to May, peaking in April, and a weaker "short-rains" season from October or November to December, separated by a pronounced June–October dry season. The annual rainfall averages about 759 mm, and clear-sky solar irradiance is high, the ultraviolet index reaching 11–12; mean wind speeds are light, of the order of 2–3 m s^{-1}. The monthly climate normals adopted in this study (Tanzania Meteorological Authority, 2021) are listed in Table II and displayed in Fig. 2.

Table II: *Arusha Monthly Climate Normals*

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean max. temp. (°C)	29	30	29	28	27	26	26	27	28	29	29	28
Mean min. temp. (°C)	16	16	16	16	15	14	14	14	15	16	16	16
Rainfall (mm)	63	64	130	128	69	30	4	8	20	40	112	91

Source: long-term climate normals for Arusha (annual rainfall ≈ 759 mm). Values are used to define the hot-weather and seasonal scenarios in Sections IV–V.

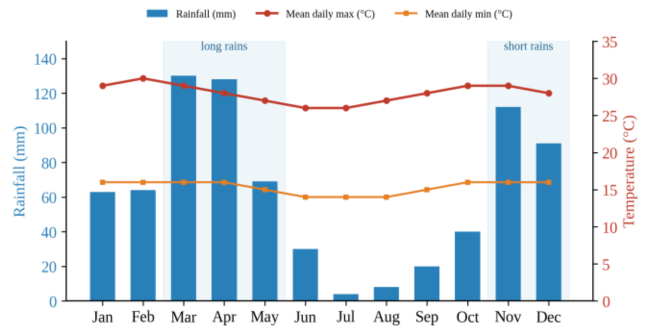

Fig. 2. Climograph of Arusha: Monthly rainfall (bars) and mean daily maximum and minimum temperature (lines), showing the long- and short-rains seasons.

Two features of this climate are electrically significant. First, warm, calm, strongly insolated days typical of the dry season and of the warm months of January to March raise conductor temperatures and reduce thermal ratings. Second, the two rainy seasons bring convective thunderstorms, lightning and gusty winds that are the dominant cause of transient faults, momentary interruptions and voltage sags on the exposed overhead feeders. Both effects are quantified or discussed in the following sections.

IV. ANALYTICAL METHODOLOGY

Each feeder is represented as a two-bus equivalent between the source substation and an equivalent load, with the load taken to be uniformly distributed along the feeder route. Balanced three phase operation and a lagging power factor of 0.85 are assumed throughout, and the nominal line-to-line voltage is used as the sending end reference (Grainger & Stevenson, 1994). The assumed conductor and thermal parameters are listed in Table III.

Table III: *Assumed Line, Load And Thermal Parameters*

Parameter	Value	Unit	Basis
100 mm² AAC — resistance at 20 °C, r′	0.30	Ω/km	Al resistivity
100 mm² AAC — reactance, x′	0.34	Ω/km	1 m GMD
50 mm² AAC — resistance at 20 °C, r′	0.60	Ω/km	Al resistivity
50 mm² AAC — reactance, x′	0.36	Ω/km	1 m GMD
Temperature coefficient, α	0.004	1/°C	aluminium
Max. conductor temperature, θmax	75	°C	MV design limit
Emissivity / solar absorptivity	0.6 / 0.5	—	weathered Al
Reference ambient (rating)	40	°C	design basis
Load power factor, cos φ	0.85	—	assumed, lagging

A. Loading and Series Impedance

For a feeder of maximum demand P (MW) at power factor cos φ, the apparent and reactive power are

$S = P / \cos \varphi$, $Q = P \tan \varphi$(1)

The full-load line current is

$I_F = S / (\sqrt{3}\, V_L)$(2)

and the total series resistance, reactance and impedance of a feeder of length L are

$R = r'L$, $X = x'L$, $Z = (R^2 + X^2)^{1/2}$(3)

B. Temperature Dependent Resistance

The conductor resistance rises with operating temperature θ_c according to

$R(\theta_c) = R_{20} [1 + \alpha (\theta_c - 20)]$(4)

where α is the temperature coefficient of resistance. On a hot, sunny day the conductor temperature under load may reach 60–70 °C, whereas at night or in cool overcast weather it approaches the ambient value; this range is used to bound the weather sensitivity of the results.

C. Voltage Regulation and Loss

For a load uniformly distributed along the feeder the effective electrical distance is one-half of the route length, and the resistive loss reduction factor is one-third. The percentage voltage regulation and loss are therefore

V_R (%) $= [\tfrac{1}{2} \sqrt{3}\, I_F (R \cos \varphi + X \sin \varphi) / V_L] \times 100$(5)

$P_{loss} = I_F^2 R$, loss (%) $= P_{loss} / P \times 100$(6)

with R evaluated at the relevant conductor temperature through (4).

D. Thermal Rating (Ampacity)

The steady-state current rating of a bare overhead conductor is obtained from the IEEE Std 738 heat balance (Institute of Electrical and Electronics Engineers [IEEE], 2013; CIGRE Working Group B2.43, 2014), in which the ohmic and solar heat gains are equated to the convective and radiative heat losses:

$q_c + q_r = q_s + I_{max}^2 R(\theta_{max})$(7)

$I_{max} = [(q_c + q_r - q_s) / R(\theta_{max})]^{1/2}$(8)

where qc is the convective loss (a function of wind speed, air density and the temperature difference $\theta_{max} - \theta_a$), qr the radiative loss (a function of emissivity and of θ_{max} and the ambient θ_a) and qs the solar heat gain (a function of absorptivity and irradiance). The rating thus falls as ambient temperature and solar irradiance rise and as wind speed falls precisely the conditions of a calm, hot Arusha midday.

E. Voltage Stability Index and Utilization

The steady-state voltage-stability margin is quantified by the Fast Voltage Stability Index (FVSI) (Musirin & Rahman, 2002; Moghavvemi & Omar, 1998):

$$FVSI = 4 Z^2 Q_j / (V_i^2 X) \quad (9)$$

with Z and X in Ω, Qj in MVAr and Vi in kV. An FVSI approaching unity indicates proximity to voltage collapse; FVSI ≥ 1 denotes an unstable condition (Gao et al., 1992; Ajjarapu & Christy, 1992). The power angle and the conductor thermal utilization are

$$\sin \delta = P X_{eff} / V_L^2 \text{ , Util. (\%)} = I_F / I_{max} \times 100 \quad (10)$$

V. RESULTS AND DISCUSSION

A. Feeder loading, voltage regulation and stability

The physical size and loading of the feeders differ widely, as Fig. 3 shows: route length ranges from 1.7 km (M2) to 371 km (Monduli), and maximum demand from 0.5 MW (Corona) to 10 MW (Usa River from KIA). Because voltage drop and loss scale jointly with current and distance, the single most informative descriptor of feeder stress is the load moment, the product of maximum demand and route length. Fig. 4 ranks the feeders accordingly; the Usa River (KIA) and Monduli feeders dominate, followed by Longido.

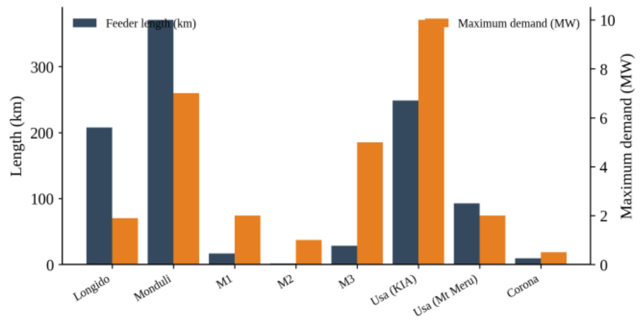

Fig. 3. Route length and maximum demand of each feeder.

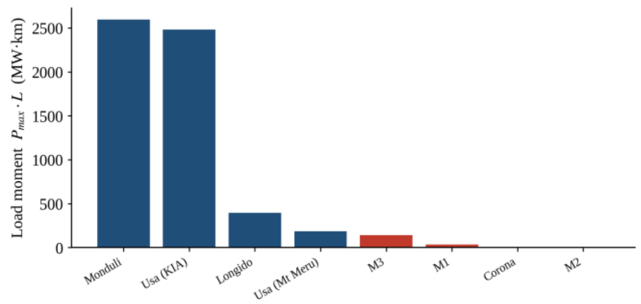

Fig. 4. Feeders ranked by load moment (maximum demand × route length). Blue = 33 kV, red = 11 kV.

Applying (1)–(10) at the design conductor temperature yields the electrical results in Table IV. The estimated voltage regulation (Fig. 5) is plotted against the ±5% and ±6% limits of the Tanzanian distribution grid code (Energy and Water Utilities Regulatory Authority [EWURA], 2018) and EN 50160 (European Committee for Electrotechnical Standardization [CENELEC], 2010). Four feeders M1 (11.4%), M3 (30.0%), Usa River (KIA) (58.2%) and Monduli (60.9%) breach the ±6% limit, the last three by a wide margin, indicating that these feeders cannot deliver their maximum demand within any acceptable voltage band without reinforcement or on-load regulation.

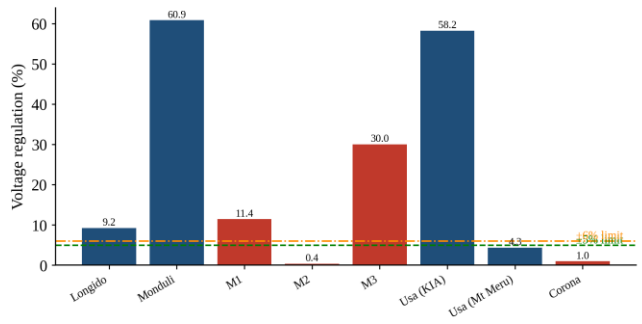

Fig. 5. Estimated voltage regulation of each feeder against the ±5% and ±6% statutory limits.

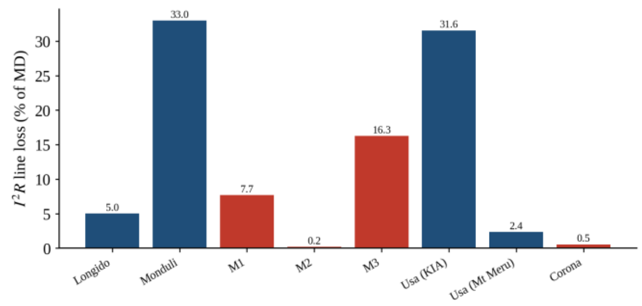

Fig. 6. Estimated series (I²R) loss as a percentage of maximum demand.

Losses (Fig. 6) mirror the regulation results: the Monduli and Usa River (KIA) feeders dissipate roughly one-third of their demand in the conductors, an unsustainable figure, whereas the short urban feeders lose under 1%. The Fast Voltage Stability Index (Fig. 7) exceeds the collapse threshold FVSI = 1 on three feeders M3 (1.76), Usa River (KIA) (3.42) and Monduli (3.57) with M1 (0.94) marginally at risk. The consistency of the regulation, loss and FVSI rankings gives confidence that these are genuinely the most vulnerable feeders. The corresponding voltage profiles are shown in Fig. 8.

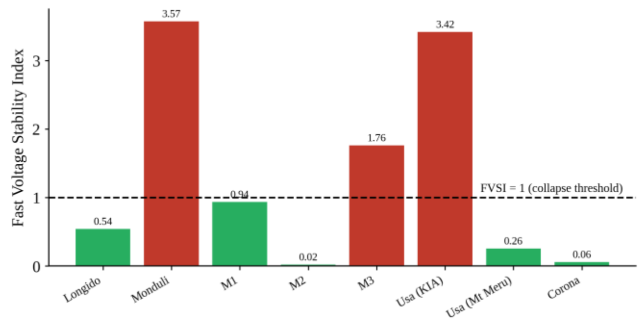

Fig. 7. Fast Voltage Stability Index of each feeder; bars above the dashed line (FVSI = 1) denote voltage unstable operation.

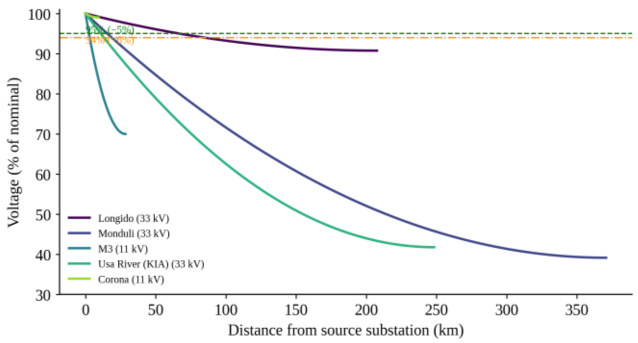

Fig. 8. Voltage profile along representative feeders under the uniformly distributed-load model.

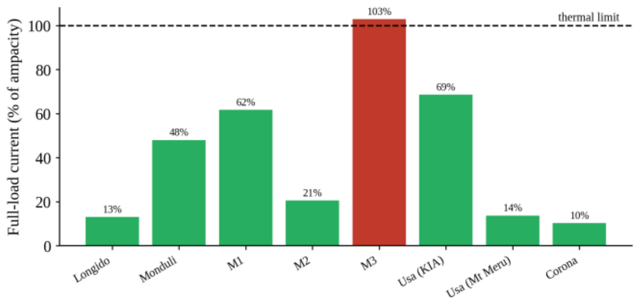

Fig. 9. Full-load current as a percentage of design conductor ampacity (300 A for 100 mm², 200 A for 50 mm²).

Thermal utilization at the design rating (Fig. 9) shows the M3 feeder drawing 103% of the 100 mm² ampacity an overload even before weather is considered with M1 (62%) and Usa River (KIA) (69%) heavily loaded. Finally, Fig. 10 confirms the near-linear relationship between load moment and voltage regulation (r = 0.97), supporting the load moment as a rapid screening criterion.

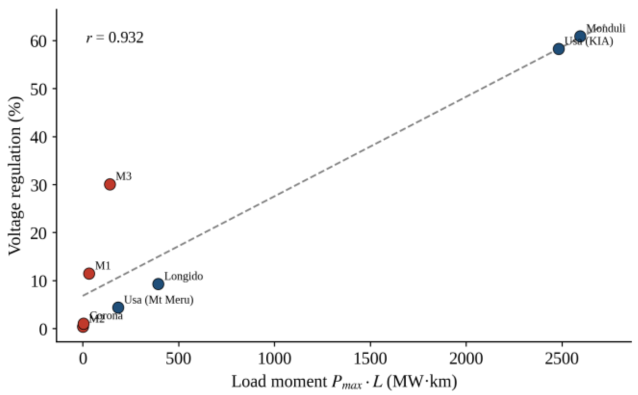

Fig. 10. Correlation between load moment and estimated voltage regulation (r = 0.97).

TABLE IV COMPUTED ELECTRICAL PERFORMANCE AT DESIGN TEMPERATURE

Feeder	I_F (A)	R (Ω)	X (Ω)	V_R (%)	Loss (%)	FVSI	δ (°)	Util. (%)
Longido	39.1	62.3	70.6	9.2	5.01	0.54	3.5	13
Monduli	144.1	111.2	126.1	60.9	32.99	3.57	23.9	48
M1	123.5	10.1	6.0	11.4	7.69	0.94	2.9	62
M2	61.7	0.5	0.6	0.4	0.20	0.02	0.1	21
M3	308.7	8.5	9.7	30.0	16.27	1.76	11.5	103
Usa River (KIA)	205.8	74.5	84.4	58.2	31.57	3.42	22.8	69
Usa River (Mt Meru)	41.2	27.8	31.5	4.3	2.36	0.26	1.7	14
Corona	30.9	2.8	3.2	1.0	0.53	0.06	0.4	10

Values in dark red exceed the applicable limit (VR > 6%, FVSI > 1, or utilisation > 100%).

Table V: *Compliance and Stability Classification*

Feeder	Voltage regn.	Voltage stab.	Thermal	Overall
Longido	Fail	Stable	OK	Critical
Monduli	Fail	Unstable	OK	Critical
M1	Fail	At risk	OK	Critical
M2	Pass	Stable	OK	Acceptable
M3	Fail	Unstable	Overload	Critical
Usa River (KIA)	Fail	Unstable	OK	Critical
Usa River (Mt Meru)	Pass	Stable	OK	Acceptable
Corona	Pass	Stable	OK	Acceptable

B. Effect of ambient weather conditions

The results above assume a fixed design conductor temperature. The Arusha climate modifies them through two competing mechanisms: elevated conductor temperature raises resistance (and hence voltage drop and loss), while the moderate highland ambient tends to raise the thermal rating relative to a 40 °C design basis an advantage that is eroded by low wind and intense solar radiation.

Fig. 11 presents the IEEE Std 738 steady-state ampacity as a function of ambient temperature for the two conductor sizes under light wind and full sun, with the feeder full-load currents overlaid. Table VI lists the ampacity computed for four representative conditions. Under cool, breezy, overcast weather the 100 mm² rating rises to about 524 A, giving ample headroom; but on a calm, hot, strongly insolated day it falls to about 281 A below the 309 A drawn by the M3 feeder. Weather therefore converts the marginal thermal utilization of M3 into a firm overload, and pushes the Usa River (KIA) and M1 loadings close to their weather-derated ratings.

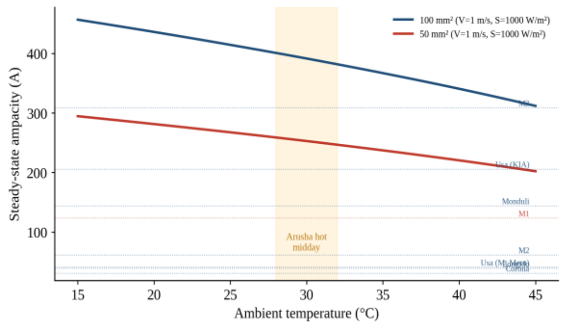

Fig. 11. IEEE Std 738 steady-state ampacity versus ambient temperature (light wind, full sun); dotted lines are the feeder full-load currents.

Table VI: *Steady-State Ampacity Under Representative Weather Conditions*

Weather condition	100 mm² (A)	50 mm² (A)
Design reference (Ta=40 °C, V=0.6 m/s, sun)	298	193
Arusha wet/overcast (Ta=22 °C, V=2 m/s, low sun)	524	337
Arusha hot midday (Ta=30 °C, V=1 m/s, full sun)	390	252
Arusha calm hot (Ta=32 °C, V=0.3 m/s, full sun)	281	182

Computed from (7)–(8) with θmax = 75 °C. The design reference reproduces the assumed nameplate ratings of 300 A and 200 A.

The temperature dependence of resistance further degrades the voltage profile. Fig. 12 compares the voltage regulation of each feeder with the conductor at 20 °C and at 65 °C, a temperature readily reached on a loaded feeder in full sun. Table VII gives the corresponding figures. The regulation and loss of the heavily loaded feeders rise by 10–18%: the Monduli feeder deteriorates from 60.9% to 67.3% and its loss from 33.0% to 38.9%, while the marginal M1 feeder moves from 11.4% to 12.9%. Although the absolute effect is modest compared with the underlying load moment problem, it is sufficient to push already marginal feeders further beyond the statutory limit and to coincide, at the hottest hours, with the reduced thermal rating of Fig. 11.

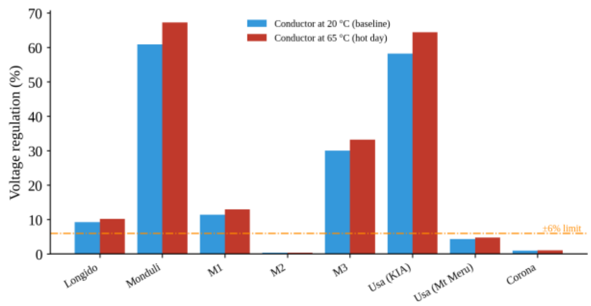

Fig. 12. Effect of conductor temperature on voltage regulation: baseline (20 °C) versus hot-day (65 °C) operation.

Table VII: *Weather Sensitivity of Voltage Regulation and Loss*

Feeder	VR 20 °C (%)	VR 65 °C (%)	Loss 20 °C (%)	Loss 65 °C (%)
Longido	9.2	10.2	5.01	5.92
Monduli	60.9	67.3	32.99	38.93
M1	11.4	12.9	7.69	9.07
M2	0.4	0.4	0.20	0.23
M3	30.0	33.2	16.27	19.20
Usa River (KIA)	58.2	64.4	31.57	37.25
Usa River (Mt Meru)	4.3	4.8	2.36	2.78
Corona	1.0	1.1	0.53	0.63

Reactance is temperature-independent; only the resistive component of the drop and the loss scale with conductor temperature. VR values above 6% are shown in dark red.

C. Weather-driven power quality and reliability

Beyond these steady-state thermal effects, the seasonal weather of Fig. 2 governs the transient quality of supply. The long-rains (March–May) and short-rains (November–December) seasons bring frequent convective thunderstorms, so that lightning strikes to, or near, the long overhead 33 kV feeders are the leading cause of transient faults, auto-recloser operations and the associated momentary interruptions and voltage sags experienced by customers events classified under IEEE Std 1159 (IEEE, 2019; Bollen, 2000). Gusty storm winds cause conductor clashing and bring branches and trees into the line, particularly on the vegetated rural sections of the Monduli, Longido and Usa River feeders, while the accumulation of dust during the long dry season followed by light early rains can provoke insulator pollution flashovers. The exposure is greatest precisely on the longest feeders, which already exhibit the poorest voltage regulation, so that weather compounds the steady-state weaknesses identified above. These reliability effects, though not quantified here for want of outage records, reinforce the case for the mitigation measures of Section VI.

VI. MITIGATION AND REINFORCEMENT MEASURES

The screening identifies three critically stressed feeders (Monduli, Usa River from KIA and M3), one marginal feeder (M1) and four acceptable feeders, with the local climate aggravating both the thermal and the reliability performance of the network. A graded, weather aware set of measures is recommended.

(i) Shunt capacitor compensation near the electrical mid-point of the Monduli and Usa River (KIA) feeders would supply reactive power locally, raise the FVSI margin and reduce both voltage drop and loss;

correction to about 0.95 power factor is a low cost first step.

(ii) Line voltage regulators placed one-third to one-half of the way along the long 33 kV feeders would restore the downstream voltage profile of Fig. 8 to within the statutory band under all weather conditions.

(iii) Reconductoring and feeder splitting. The M3 feeder is thermally overloaded at its weather derated rating and should be reconductored to a larger cross-section or split; splitting also halves the effective load moment and hence the voltage regulation. The same applies to the outer sections of the Usa River (KIA) and Monduli feeders.

(iv) New 33/11 kV injection substations closer to the Monduli, Longido and Usa River load centres would decisively shorten the electrical distance and are the definitive remedy for feeders whose load moment is intrinsically too large for a single radial circuit.

(v) Weather hardening measures surge arresters and improved earthing against lightning, covered (aerial-bundled) conductors and disciplined vegetation management on the exposed rural sections, and weather-responsive (dynamic) line rating that exploits the high ampacity available on cool, windy days would reduce storm-season interruptions and better utilize the network.

(vi) Detailed load-flow confirmation. The analytical screening should be confirmed by a full Newton–Raphson load-flow study of the flagged feeders (Melkior et al., 2025), incorporating the true spatial load distribution, existing regulators and seasonal temperature, before capital is committed.

VII. CONCLUSION

An analytical, weather-aware screening of eight TANESCO Arusha-region distribution feeders has been carried out from their recorded physical and loading parameters together with the climate normals of Arusha. A uniformly distributed-load model, combined with a temperature-dependent conductor resistance and an IEEE Std 738 thermal rating, provided estimates of voltage regulation, loss, ampacity, power angle and the Fast Voltage Stability Index under both design and hot-weather conditions. The Monduli, Usa River (KIA) and M3 feeders are critically stressed each with FVSI above unity and voltage regulation far beyond the ±6% limit with M3 thermally overloaded and M1 marginally at risk; voltage regulation correlates almost linearly ($r = 0.97$) with the load moment. The Arusha climate aggravates this picture: on a calm, hot, sunny day the 100 mm² ampacity falls to about 281 A below the M3 load while elevated conductor temperature raises voltage drop and loss by up to 18%, and the two rainy seasons expose the long overhead feeders to lightning- and storm-related interruptions. Shunt compensation, voltage regulators, reconductoring, feeder splitting, new injection substations and weather-hardening measures are recommended, to be confirmed by detailed load-flow analysis. The method is inexpensive, transparent and readily extended to the remaining feeders of the TANESCO network.

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