Part of Energy Queensland

# Network Standard

# Standard for Plant Energisation

If this standard is a printed version, to ensure compliance, reference must be made to the Ergon Energy or Energex internet site to obtain the latest version.

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Abstract: This standard details the voltage impact requirements for plant such as transformers, reactors and capacitor banks undergoing energisation on the Ergon Energy or Energex distribution networks.

Keywords: Voltage, Energisation, Transformer, Capacitor Bank, Generator

# Standard for Plant Energisation

For definitive document version and control detail, please refer to the information stored on the Process Zone.

## Revision history

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## Document approvals

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# 1 Overview

## 1.1 Purpose

This standard is to be used to define acceptable voltage impacts of customer electrical plant energisation, to ensure a balance between difficult to meet requirements for proponents and acceptable power quality for all network users.

Transient currents and voltages from energisation activities can lead to power quality issues in terms of non-compliance with the defined acceptable voltage limits, and in extreme cases, produce insulation degradation or surge arrestor failure. Exceedance of the high voltage limit can lead to nuisance tripping, equipment damage and failure. Likewise voltage dips below the acceptable limits may lead to industrial processes malfunctioning, damage to customer equipment or shutting down as well as protection operation.

## 1.2 Scope

This document details the physics behind energisation inrush, modelling procedure and considerations, and acceptance criteria when authorisation of energisation of a power transformer or other electrical plant onto the Ergon Energy or Energex networks.

It is not intended to cover voltage fluctuations caused by loads or motor starting as examined in AS/NZS 61000.3.7.

It is not intended to be applied retroactively to existing connections.

### 1.2.1 Energisation

When electrical plant is energised, the grid will experience a transient phenomenon known as “inrush current”. This is primarily associated with transformers but can also exist for plant such as capacitor filter banks. In a transformer, inrush is caused by the iron core of the transformer reaching saturation due to the abrupt voltage change applied to it and the point on the wave that the transformer energised. When saturated, the transformer absorbs a magnetisation current (i.e. the inrush current), which can reach several times the nominal current of the transformer. This inrush current results in a voltage drop across the source impedance (sometimes commonly called a voltage dip or fluctuation). For a large transformer connecting to a weak grid, unacceptable voltage dips may occur, and therefore must be adequately studied and mitigated. In addition, sympathetic inrush may occur in nearby transformers, causing wider system voltage dip effects, and harmonic resonance induced by energisation may lead to unacceptable overvoltage under certain system conditions.

# 2 References

## 2.1 Energex controlled documents

| Document number or location (if applicable) | Document name | Document type |
|---|---|---|
| 01807 | Standard for Connection of Embedded Generating Systems to a Distributor’s HV Network | Standard |
| 03510 | Standard for Network Performance | Joint Standard |
| 03514 | Common Transmission and Distribution Planning Guidelines | Joint Standard |

| | | |
|---|---|---|
| | | |

## 2.2 Ergon Energy controlled documents

| Document number or location (if applicable) | Document name | Document type |
|---|---|---|
| STNW1175 | Standard for Connection of Embedded Generating Systems to a Distributor's HV Network | Standard |
| STMP001 | Standard for Network Performance | Joint Standard |
| STMP003 | Common Transmission and Distribution Planning Guidelines | Joint Standard |

## 2.3 Other documents

| Document number or location (if applicable) | Document name | Document type |
|---|---|---|
| Cigre 568 | Transformer Energization in Power Systems: A Study Guide | Technical Reference |
| Cigre 412 | Voltage Dip Immunity of Equipment and Installations | Technical Reference |
| AS/NZS IEC/TR 61000.2.8 | Electromagnetic compatibility (EMC)<br>Part 2.8: Environment—Voltage dips and short interruptions on public electric power supply systems with statistical measurement results | Standard |
| IEEE 493 | IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems | IEEE Recommended Practice |
| SA/SNA TR IEC 61000.3.15 | Electromagnetic compatibility (EMC)<br>Part 3.15: Limits—Assessment of low frequency electromagnetic immunity<br>and emission requirements for<br>dispersed generation systems in LV network | Standard |
| AS 60038 | Standard Voltages | Standard |
| 61000.3.100 | Limits—Steady state voltage<br>limits in public electricity systems | Standard |
| AS/NZS 4777.2 | Grid connection of energy systems via inverters | Standard |
| AS/NZS 61000.3.7 | Limits- Assessment of emission | Standard |

| | | |
|---|---|---|
| | limits for fluctuating loads in MV and HV power systems | |
| ENA Engineering Recommendation P28 | Voltage fluctuations and the connection of disturbing equipment to transmission systems and distribution networks in the United Kingdom | Technical Reference |

# 3 Legislation, regulations, rules, and codes

| Legislation, regulations, rules, and codes |
|---|
| National Electricity Rules |
| Queensland Electricity Regulation |
| Queensland Electricity Act |

# 4 Definitions, acronyms, and abbreviations

## 4.1 Definitions

For the purposes of this standard, the following definitions apply:

| Term | Definition |
|---|---|
| acceptable model | a site-specific model which follows the requirements of AEMO's Power System Model Guidelines |
| committed | • AEMO has issued a letter to the connecting NSP under clause 5.3.4A of the NER indicating that AEMO is satisfied that each specified access standard meets the requirements applicable to a negotiated access standard under the NER;<br>• an offer to connect has been issued by the Connecting NSP in accordance with clause 5.3.6 of the NER;<br>• AEMO and the connecting NSP for that other proposed connection have accepted a detailed PSCAD™/EMTDC™ model provided by or on behalf of the Connection Applicant of that proposed connection meets the requirements of the Power System Model Guidelines;<br>• any proposed system strength remediation schemes or system strength connection works in respect of that other proposed connection have been agreed between the relevant parties, or determined by a dispute resolution panel; and<br>• there is no reasonable basis to conclude that the model previously provided is materially inaccurate, including following commissioning of the connection. |
| Detailed response to enquiry | a detailed, in-depth analysis and considerations for the particular proposed project and enabling the proponent to move towards submitting an Application to Connect |
| collector transformer | In a renewable generation plant, inverter units aggregate up to a low voltage: medium voltage transformer, as an example, 550V to 33kV. |
| electrically close | up to 200km away as measured through the electrical system |
| generator | Has the meaning given in the NER. Broadly this is a person who engages in the activity of owning, controlling or operating a generating system that is connected to and/or supplies electricity to Ergon Energy's or Energex's distribution network. |
| micro EG | Refers to a generating system with generating units of the kind contemplated by AS 4777 as per 5A.A.1 of the NER |

## 4.2 Acronyms and abbreviations

The following abbreviations and acronyms appear in this standard.

| Acronym | Definition |
|---|---|
| AC | Alternating Current |
| AEMC | Australian Energy Market Commission |
| AEMO | Australian Energy Market Operator |
| AVR | Automatic Voltage Regulation |
| CB | Circuit Breaker |
| CBF | Circuit Breaker Fail |
| CBD | Central Business District |
| DC | Direct Current |
| EG | Embedded generator/ generating unit |
| EMT | Electromagnetic transient |
| FCAS | Frequency Control Ancillary Service |
| GPR | Grid Protection Relay |
| GPS | Generator Performance Standard |
| HV | High voltage. A voltage exceeding 1,000 V AC and 1,500 V DC. |
| IES | Inverter Energy Systems |
| LDC | Line drop compensation |
| LV | Low voltage. A voltage not exceeding 1,000 V AC or 1,500 V DC. |
| MEGU | Micro-embedded generating unit |
| NCP | Network Coupling Point |
| NER | National Electricity Rules |
| OH | Overhead conductor, “lines” |
| POE10 | Forecasting; 10% Probability of Exceedance |
| PSCAD™/EMTDC™ | Refers to a software package developed by the Manitoba-HVDC Research Centre that comprises a power systems computer-aided design package which includes an electromagnetic transients (including DC) simulation engine, and which is used to carry out electromagnetic transient type studies. |
| p.u. | Per unit |
| ROCOF | Rate of change of frequency |
| RPEQ | Registered Professional Engineer of Queensland |
| SACS | Substation Automated Control System |
| SCR | Short Circuit Ratio |
| UG | Underground conductor, “cables” |
| VVR | Volt Var Regulation |
| ZS | Zone Substation |

# 5 Summary of Requirements

The maximum acceptable voltage drop or overvoltage effect on energisation is shown in Table 1:

**Table 1 - Plant Energisation Acceptance Criteria**

| All Connections[1] |
| --- |
| • Voltage dip or overvoltage spike remains within 0.9pu to 1.1pu<br>• The voltage returns to 95% of pre-disturbance voltage within 200ms<br>• Must not cause existing or committed generating systems to enter fault ride through mode<br>• Collector transformer energisation to comply with the allocated flicker limit[2] |

## 5.1 Measurement and Verification

For all large customers, a power quality meter (primarily for the purposes of harmonic and flicker compliance) shall be installed at the appropriate location as close to the point of connection as practicable, noting the connection arrangement of VTs so that any energisation event can be recorded and reviewed.

## 5.2 Report Requirements

A plant energisation report is to be provided at the application stage to demonstrate compliance with Table 1. This may cover transformers and collector transformers, harmonic filters, or other electrical plant if relevant. It is not intended to include analysis of voltage fluctuation caused by repeated processes such as drilling or pumping.

Ergon Energy and Energex expect methodology consistent with industry standards listed in the Reference section.

The following aspects shall be represented:

- Leakage impedance and winding resistance;
- Nonlinear saturation and core losses (Air-core inductance);
- Magnetic phase coupling;
- Residual flux in transformer cores;
- Appropriate consideration and representation of Zero Sequence Impedance for the transformer;
- Hysteresis and frequency dependent iron losses.

The report shall detail:

- Description and extent of the network modelled;
- Assumptions made;
- System normal, minimum system strength and contingency (N-1) scenarios in the upstream network that represent worst case with discussion in the report as to why these are considered worst case;
- Consideration of sympathetic inrush in other transformers or capacitors in the network;
- Consideration of harmonic resonance;
- Details of the BH curve used for the transformer(s); where a BH curve is not available or not yet available, appropriate literature supported assumption on suitable approximations for BH curve should be used.

[1] 11kV, 22kV and 33kV connected generating systems may not have a grid connection power transformer but will have step-down transformers associated with the collector network systems. These transformers may also cause inrush effects and so must be studied. Additionally, these systems may have harmonic filters installed.

[2] Guidance on this is provided in Section 6.5

- Capacitance information of capacitor banks, with any inrush reactors if relevant;
- Where the transformer is for a renewable generation site, inclusion of energisation of the collector feeder transformers and a comparison of individual energisation or all being energised at once, including sympathetic effects;
- Results showing the following profiles and differences for each of the scenarios with extended tails up to 7 seconds if required (preferably in a table format):
  - 50 Hz voltage
  - peak phase voltage
  - RMS voltage drop for line to neutral voltages
  - 50Hz levels/peak voltage/RMS step represented as a table
- A table which clearly states the buses studied, the pre-energisation voltage, the maximum line to ground voltage dip, and the maximum transient current and period of time before the source voltage returns to 95% of pre-energisation and then to the pre-energisation voltage; and
- A graph that clearly displays the RMS Percentage of Voltage over time from energisation of transformer to the time it takes to return within 1% of the pre-disturbance voltage.
- The conclusion of the studies in comparison with this standard. Where the studies identify that the standard is not met, then the report shall detail remediation considered and recommended for the location and the modelled effectiveness and subsequent compliance with this standard, such as provision for point on wave switching, pre-insertion resistors, and other mitigation measures.

# 6 Transformer Energisation Inrush

## 6.1 Theory

Power transformer inrush current is a phenomenon that occurs when a transformer core becomes saturated. This can be caused by switching transients, out-of-phase synchronisation of a generator, external faults, fault clearance or energisation. The most severe case is when a transformer is initially energised by applying a voltage, switching at voltage zero crossing for one phase, whilst the transformer core holds a residual flux, where the flux in the core can reach a maximum two times the rated peak flux plus the residual flux offset.

**Residual flux is the flux that remains after a transformer has been de-energised whilst still holding some degree of magnetism. The current is determined by the flux-linkage, which is calculated as the time-integral of the voltage applied to the transformer. The initial value of the flux-linkage is determined by the residual flux in the transformer core prior to energisation. The flux-linkage/current relationship is nonlinear and is determined by the saturation curve of the transformer. This is represented in**

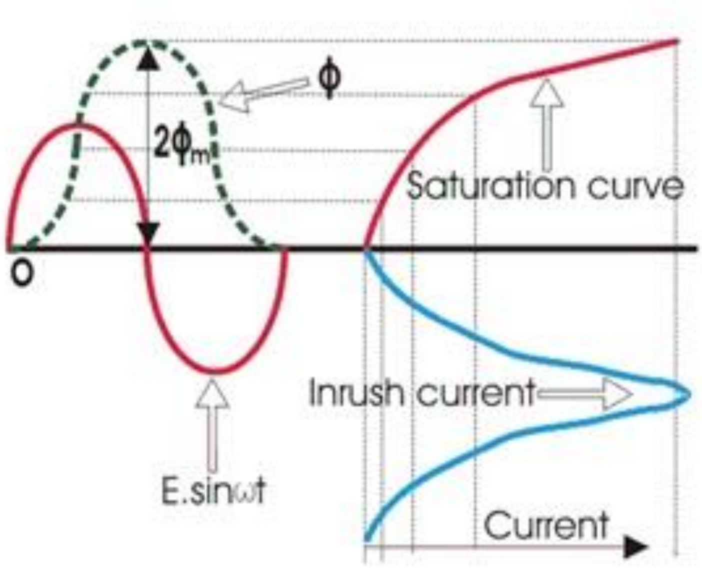


Figure 1 below.

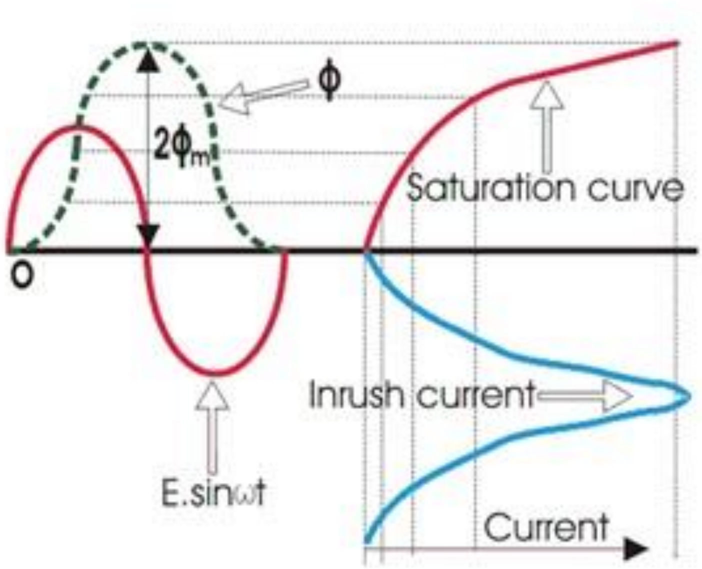


**Figure 1 - Inrush Current vs Saturation Curve vs Applied Voltage[3]**

The main factors affecting the inrush current magnitudes can categorised as: transformer design, initial conditions, and network factors.

[3] Source: Electrical 4 U

The design of a transformer can affect the magnitude of the inrush current as it can shift the steady state operating point on the saturation curve. A transformer with an operation point closer to the knee area of the saturation curve is easily brought into saturation.

Initial conditions affecting the magnitude of inrush current are residual flux and the point-on-wave (POW) energisation. These influence the magnitude of inrush currents and affect the DC offset of the flux-linkage and the saturation of the transformer. The residual flux is the flux that remains trapped in the core due to a previous de-energisation of the transformer and defines the initial DC offset of the flux in the core. Energisation at a voltage zero crossing results in the most severe inrush current for a transformer as it induces a flux-linkage of theoretically up to 2 p.u. (with 1 p.u. DC offset); the residual flux adds on top of that giving a maximum possible flux-linkage of almost 3 p.u. Energising a transformer at voltage peak results in no DC offset other than that caused by the initial residual flux.

High network impedance acts as a limiting factor for inrush current. The high current causes a voltage drop at the transformer terminals which limits the saturation of the transformer.

Transformer energisation is covered in more detail in Annex A - Detailed Transformer Energisation Theory below.

## 6.2 Harmonic Current Resonances

Transformer saturation is a highly nonlinear phenomenon. Hence, the inrush current contains harmonic and DC components besides the fundamental component. To obtain the magnitude and phase shift of each harmonic component, a Fourier analysis should be conducted for each cycle of the inrush current separately. In some cases the duration of the harmonic components can attain their maximum value a few cycles after energisation, or experience a phase shift as the magnitude of the harmonic passes through zero. If the harmonic currents coincide with a parallel resonance in the frequency dependent impedance of the network it can result in overvoltages, causing wider problems in the network for other network users, and may result in protection mal-operation where the protection has not been designed to account for energisation phenomenon. The maximum overvoltage often occurs during the decay of the inrush current and not immediately after energisation, when the individual harmonics attain their maximum values.

The spectrum of harmonic currents cannot be generalised as it depends highly on the transformer, feeding network, and initialisation conditions. Therefore a case-by-case study is required for each specific transformer. The harmonics are generally low order, peaking at the second harmonic. An impedance scan looking into the network might indicate whether there is a risk of transformer inrush current exciting harmonic overvoltage (for example if a parallel resonance resides below ~7th harmonic).

## 6.3 Sympathetic Interaction

Sympathetic interaction can occur when a transformer or shunt reactor is energised onto a system with long transmission lines in the presence of other electrically close and energised transformers or shunt reactors (noting shunt reactors typically have air gaps in the iron core (or they are air cored reactors for transmission lines) which means they will not significantly saturate and will have a reasonably linear behaviour during energisation) . Sympathetic interaction significantly changes the duration and the magnitude of the transient magnetising currents in the transformers involved. Transformers are typically energised in series or in parallel with other transformers already in service. On systems with appreciable series resistance, this inrush transient may trigger a transient interaction between the transformer being energised and those already in operation. This occurs because the existing transformers go into saturation, produced by asymmetrical voltage waveforms at the busbar due to the asymmetrical voltage drop across the series resistance of the system caused by the inrush current. This shall be considered as part of the transformer energisation study.

### 6.4 System Strength

System strength also has an impact on the effect of energisation. Systems with high system strength will experience less voltage dip than systems with lower system strength as there is less impedance in the system and therefore reduced voltage drop.
Areas with very low system strength will reach a tipping point, where the inrush current is limited and is lower than in a stronger system and voltage dip effects do not become more pronounced. However, the voltage dip will then be sustained for a longer period of time.
Aside from inrush current magnitude and subsequent voltage dip, system strength also impacts harmonic currents and resonances in the network, which can exacerbate transformer energisation effects.
System strength is of relevance to the Ergon Energy and Energex networks, as there are locations with very low short circuit ratio to transformer size (in some cases, less than SCR 2).

### 6.5 Collector Transformers

Renewable energy generators generally have a large grid-connection power transformer, and then a number of collector feeders, where output from a number of inverters or turbines are aggregated. A transformer is required to step-up the output of the inverter to the distribution voltage of the plant (usually, 22kV or 33kV). Often these collector transformers are small (typically 2.5-6MVA) and may have a different copper/steel mix to other power transformers. This can affect the energisation behaviour of the transformers and the knee-point of saturation. As such, the impact of a 5MVA transformer can be similar to a larger power transformer. Therefore, this must also be studied, and the resultant voltage dip considered in the context of the flicker allocation, as the energisation will be repeated over a day (or longer) until all the collector transformers are energised. Sympathetic inrush as subsequent transformers are energised shall also be considered.

The following table is provided as guidance for interpreting the flicker allocation in relation to voltage dips associated with numerous energisation events.

**Table 2 - Emission limits for voltage changes in function (Table 7 from AS/NZS 61000.3.7:2001)**

| r (/hour) | $\Delta U_{dyn}/U_N$ (%) | |
|---|---|---|
| | MV | HV |
| r ≤ 1 | 4 | 3 |
| 1< r ≤10 | 3 | 2.5 |
| 10 < r ≤100 | 2 | 1.5 |
| 100 < r ≤1000 | 1.25 | 1 |

## 7 Methodology of Modelling for Transformer Energisation

Numerical Methods and electromagnetic-transient methods can be used for modelling of the effects of transformer energisation including identifying peak inrush current, maximum voltage dips, and current and voltage recovery times.

### 7.1 Numerical Method - Preliminary Studies

Numerical Methods can only accurately be used to estimate single phase system inrush currents, voltage dips and recovery times. The reason for this is the complexity required to estimate a three-phase system which would need to include the interaction of multiple coils and the residual flux interacting with each of the three phases. Adding to this, independent switching of the circuit breaker poles will then introduce further complexity with regards to massive negative sequence currents arising as a result of the individual switching of the phases.

One numerical method has been detailed in Annex B of this Standard. Industry papers, such as ENA ER P28, Cigre 568 and others, also detail numerical methods of energisation.

Numerical methods should only be used to gauge general risk of a transformer energisation and should not be used as a basis for design.

### 7.2 EMT (Electromagnetic Transient) Modelling

Energisation of the transformer can also be modelled using PSCAD/EMTDC or equivalent EMT software. A network model must be built, and the transformer model created. This network model must be sufficient to assess the impact to other connected customers; for example, the model extent and methodology should allow for assessment of voltage dips at connection points for other customers in the vicinity of the transformer being studied, possible sympathetic inrush in nearby transformers and harmonic overvoltages during the inrush transient.
Transformer core saturation should be modelled with careful consideration given to assigning values to parameters where test or theoretical data is unavailable. There are two main methods by which transformers are modelled in PSCAD; the Classical Approach and the Unified Magnetic Equivalent Circuit (UMEC) method. The classical models are limited to single phase units where the different windings are on the same leg of the core, while the UMEC models consider the core geometry and represent inter-phase coupling.
The primary difference between these two models relates to how core non-linearity is represented. In the Classical models, the non-linear characteristics are approximated based on the knee point, air core reactance and magnetising current at rated voltage; core saturation is modelled using a compensating current source across the winding closest to the core. The UMEC model requires the non-linear core characteristics to be entered directly as a piece-wise linear V-I (rms) curve.
The more sophisticated saturation models suffer from the disadvantage that in most practical situations, the data is not available to make use of them, e.g. the saturation curve is rarely known much beyond the knee, and detailed transformer design data such as core and winding dimensions may not be available.

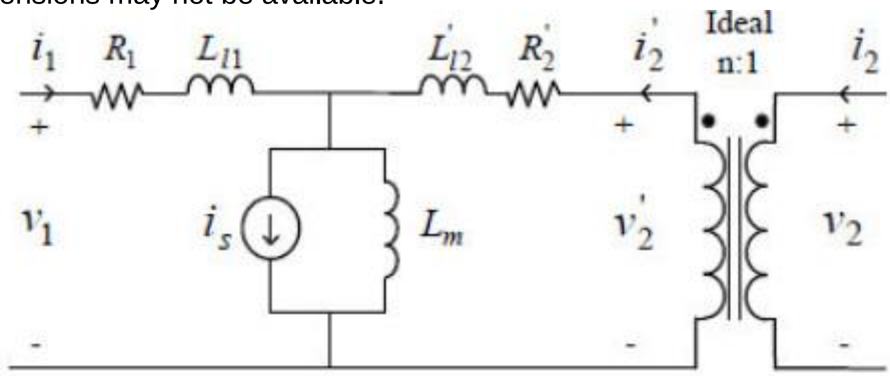


**Figure 2 - Classical Approach - Transformer Model[4]**

This modelling should consider the theoretical worst-case conditions, in order to determine the worst-case scenario. For example, the studies should consider minimum system fault levels, worst case point on wave switching and worst case theoretical residual flux in the transformer cores. Where assumptions are made, the studies should demonstrate the sensitivity of the assumption (e.g. for an assumed air core reactance, studies should show the sensitivity in results when varying the air core reactance within the typical range).

The following aspects need to be represented in the EMT model:

- Leakage impedance and winding resistance;
- Nonlinear saturation and core losses (Air-core reactance);
- Magnetic phase coupling;
- Residual flux in transformer cores;

[4] Source - https://www.pscad.com/

- Appropriate consideration and representation of zero sequence impedance for transformer type;
- Hysteresis and frequency dependent iron losses

All generation proponents, or load customers with (a) large transformer(s) shall submit the results of the EMT transformer energisation study at the Application to Connect stage.

# 8 Energisation of Capacitor Banks

When a capacitor bank is energised, inrush current and overvoltages can result. The total inrush current combines the steady state load current of the capacitor bank, with the inrush from the system, as well as any sympathetic inrush from adjacent banks.

The inrush current can be represented by:

$$I_{peak} = \frac{V_{peak}}{Z_C}$$

$$Z_C = \sqrt{\frac{L}{C}}$$

$$f = \frac{1}{2 \cdot \pi\sqrt{LC}}$$

Where:
$I_{peak}$ = peak inrush current;
$V_{peak}$ = peak voltage;
f = transient frequency.

In addition, the inrush from the system, and the sympathetic inrush from adjacent banks must be included.

This large inrush current can result in a significant voltage dip. One method of mitigation of these inrush current is with the installation of an inrush reactor.

Immediately following the voltage dip, the system voltage will attempt to recover, but will over-shoot the normal system voltage by an amount that is nearly equal to the voltage dip. Theoretically, two per-unit over-voltages can occur due to capacitor switching.

A report detailing the energisation effect of a capacitor bank shall include:

- Parameters and design of the capacitor bank,
- Internal network of the plant,
- Considerations of sympathetic inrush from nearby capacitor banks,
- Effect of transformer tapping,
- Consideration for harmonics,
- Voltage impacts on the wider network.

# 9 Legislative Requirements

Voltage regulation in Queensland is defined by the Queensland Electricity Regulation.

For a low-voltage system, 11(4) of the Regulation defines the standard voltage as the nominal voltage as stated in AS60038. 13(3)(a) and (b) specifies that changes of voltage at a customer's terminals, 'does not differ from the standard voltage by more than the percentage stated for the supply voltage range in AS60038; or otherwise is within the minimum preferred steady state median voltage and the maximum preferred steady state median voltage stated in AS 61000.'

For a supply at high voltage, clause 12 of the Regulation states that the agreed voltage is the standard voltage for supply, and 13(4) defines that for voltages of 22,000V or less, the high voltage is to be maintained at no more than 5% more or less than the standard voltage, while for voltages more than 22,000V, within an agreed margin.

For both scenarios, the methodology for measurement of steady state voltage stated in AS61000 (i.e. 61000.3.100) applies.

This gives a probabilistic limitation for transient events, rather than a fixed deterministic requirement.

## 9.1 Voltage Fluctuations - National Electricity Rules

At present, in Queensland, derogation 9.37.12 applies with reference to voltage fluctuation, replacing clause S5.1.5.

> "A Network Service Provider whose network is a Queensland transmission network or a Queensland distribution network must ensure that voltage fluctuations caused by the switching or operation of network plant does not exceed the following amounts referenced to Figure 1 of Australian Standard AS 2279, Part 4:
>
> 1) Above 66kV:
>    A. the "Threshold of Perceptibility" when all network plant is in service; and
>    B. the "Threshold of Irritability" during any credible contingency event which is reasonably expected to be of short duration;
> 2) 66kV and below: the "Threshold of Irritability" when all network plant is in service.
>
> The requirements of paragraphs (1) and (2) above do not apply to events such as switching of network plant to or from an abnormal state or to network faults which occur infrequently (i.e. less than one event per day).
>
> Each Customer must ensure that variations in current at each of its connection points including those arising from the energisation, de-energisation or operation of any plant within or supplied from the Customer's substation are such that the contribution to the magnitude and rate of occurrence of the resulting voltage disturbance does not exceed the following limits:
>
> (i) where only one Customer has a connection point associated with the point of supply, the limit is 80% of the threshold of perceptibility set out in Figure 1 of Australian Standard AS2279, Part 4; or
>
> (ii) where two or more Distribution Network Service Providers or Customers causing voltage fluctuations have a connection point associated with a point of supply, the threshold of perceptibility limit is to be shared in a manner to be agreed between the Distribution Network Service Provider and the Registered Participant in accordance with good electricity industry practice that recognises the number of Registered Participants in the vicinity that may produce voltage fluctuations."

The derogation clearly calls out Figure 1 from AS2279.4 and not the standard itself which is in fact obsolete. It is important for a generator customer, connecting under 5.3A of the National Electricity Rules to ensure they comply with the requirements of S5.2.5.2 for their connection. This must be in harmony with the derogation 9.37.12. However it is recognised that some consideration of frequency and impact to other customer connections may need to be taken which this standard addresses.

## 9.2 Voltage Swell Limitations - National Electricity Rules

A voltage swell is a temporary increase of the voltage at a point in the electrical system above 14% of the nominal voltage. Voltage swells are described by duration and maximum voltage. They may last from half a cycle to 60 seconds. If the voltage continues to be greater than 10% after 60 seconds, it is defined as Overvoltage. Overvoltage should be read in conjunction with Voltage Swell. For Energy Queensland, the limit for voltage swells is defined by Figure S5.1a.1 of the National Electricity Rules (NER):

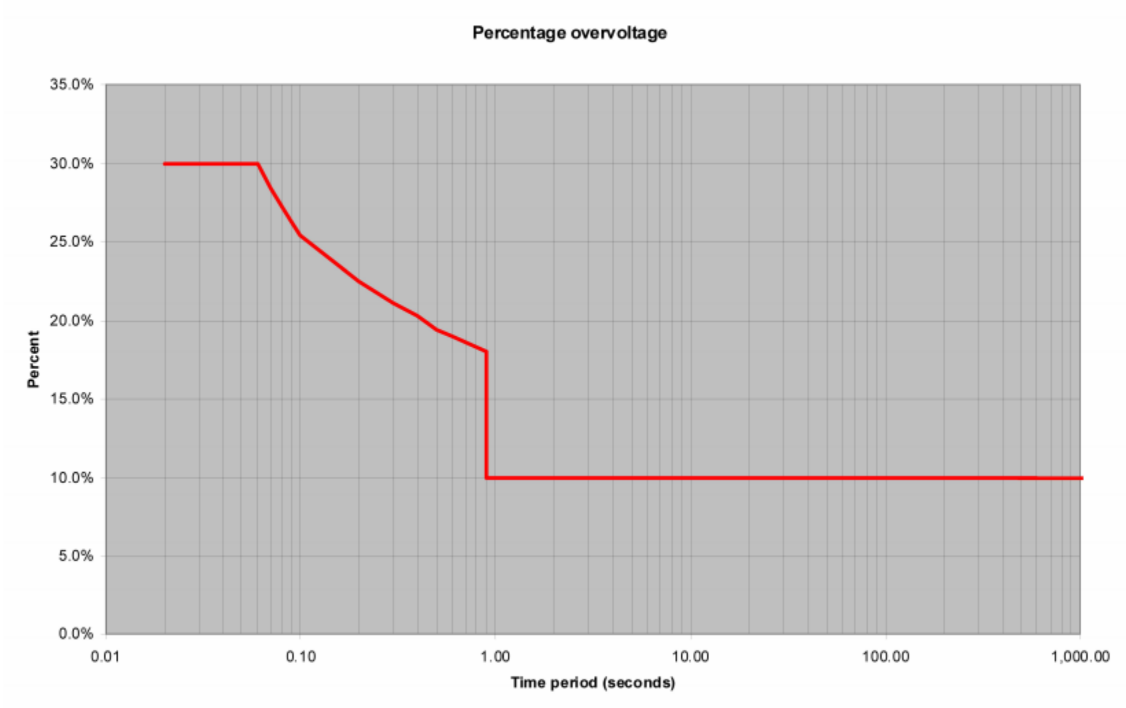


**Figure 3 - Percentage overvoltage permissible**

# 10 Voltage Dip Limitations

Voltage dips, or sags, are short-duration reductions in voltage magnitude. These dips can have an impact on end-use equipment. Industrial processes may malfunction or shut down due to a voltage dip, resulting in financial losses or equipment damage. As such, it is a requirement that network service providers keep voltages within certain limits as described in the Queensland Electricity Regulation.

Equipment withstand capability is subject to a number of standards, particularly IEEE 493 and SA/SNA TR IEC 61000.3.15. Withstand capabilities for transients are not well-defined.

Equipment immunity is affected by both the voltage related parameters such as pre-disturbance voltage magnitude, dip duration, dip magnitude and the post-dip recovery, as well as specific hardware parameters and the load type. As such, criteria for acceptability must include reference to both the magnitude of a dip, as well as the duration.

Transformer energisation is an aperiodic event- that is, once it occurs, it is not expected to occur again for some time. Hence, typical methods of measuring flicker are not applicable.

Given the size and diversity of the Ergon Energy and Energex networks, it must be assumed that not all devices connected comply with equipment withstand standards. There are numerous synchronous and asynchronous motors that are connected to the network. AS61000.2.8 identifies that asynchronous motors are generally tolerant to residual voltage of 70% of rated voltage, while synchronous motors may only be tolerant to 75%.

Generators likewise are affected by voltage dips. Generators fall in to two categories:

- Smaller systems, which do not maintain operation during a dip scenario (typically LV connected) as detailed in section 10.1 below
- Larger systems, which have low-voltage ride through capability of residual voltage of 70%-80% for two seconds

For systems with low-voltage ride through capability, a voltage dip event such as a result of transformer energisation forces the generator into ride-through mode. This causes the generator to vary its normal response. While this is expected to occur during genuine faults, to deliberately cause such a fault response is seen as 'causing harm' and must be avoided.

## 10.1 Small Generator Shake-Off

Small generating systems compliant with AS4777.2:2015 have an undervoltage protection function for anti-islanding reasons and will trip after 1s at 180V (0.78p.u. for 230V nominal). As penetration of small generation increases, generator "shake-off" presents a risk to power system security.

# Annex A Detailed Transformer Energisation Theory

Power transformer inrush current is a phenomenon that occurs when a transformer is initially energised by applying a voltage whilst the transformer core holds a residual flux/magnetism[5]. Residual flux is the flux that remains after a transformer has been de-energised whilst still holding some degree of Magnetism (denoted by the unit B (Tesla)). An example of this is by looking at the hysteresis curve in Figure 4.

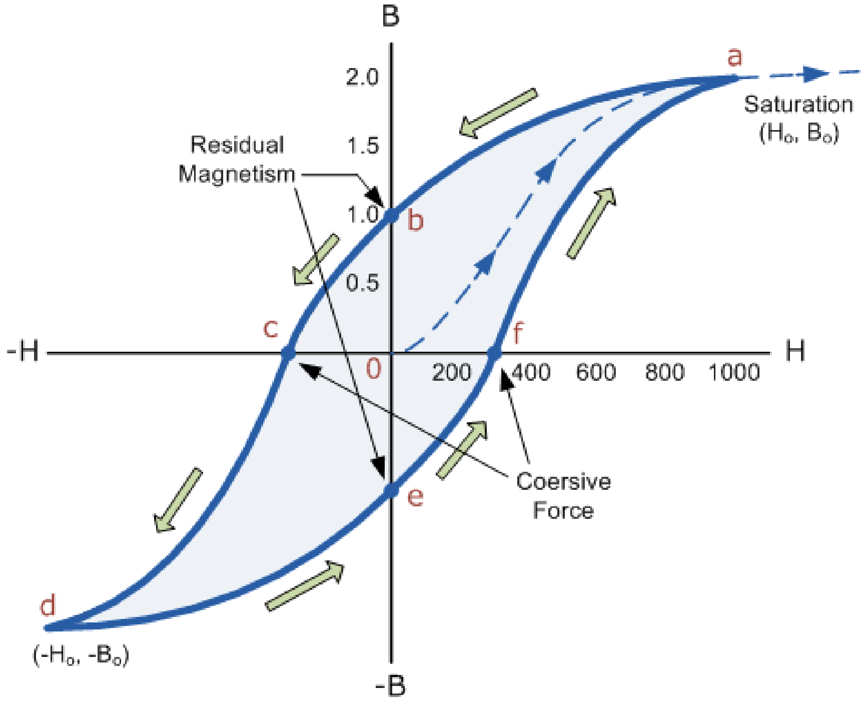


**Figure 4- Hysteresis Loop for Magnetism (Electronics Tutorials n.d.)[6]**

The arrows in Figure 4 represent a sinusoidal voltage waveform. The Y-intercept of this figure represents an angle of 0° in the waveform. If the transformer is de-energised with the voltage waveform at 0°, a residual flux or magnetism will be held in the transformer. This is due to the alignment of the dipole molecules in the metal core, which will always align their polarity in the direction of magnetic fields. For simplicity, only the main loop has been shown here, other resultant minor B-H loops have not been included.

In essence, an external force (or 'coercive force') must be applied on these dipole molecules in order to force their positioning/alignment into a random order that results in the cancellation of the magnetic fields they create, as opposed to the strengthening of the magnetic field. If the correct coercive force is not applied to the transformer core, the core will hold a residual flux after its de-energisation.

This is relevant to transformer inrush current as the unit H (Henry) is also denoted as the unit Amperes/Metre, which is directly proportional to the magnetisation current. This means that as the voltage increases and decreases on the hysteresis loop, so does the magnetisation current.

The saturation curve can also be described by magnetic flux and magnetising current, as represented in Figure 5.

[5] It is noted that inrush current will occur regardless of the residual flux, it is the outcome which worsens depending on the value and sign of the residual flux

[6] https://www.electronics-tutorials.ws/electromagnetism/magnetic-hysteresis.html

The current increases substantially as the voltage begins to enter the saturation region. This is known as the inrush current and occurs once almost all of the dipole molecules in the ferromagnetic transformer core are aligned.

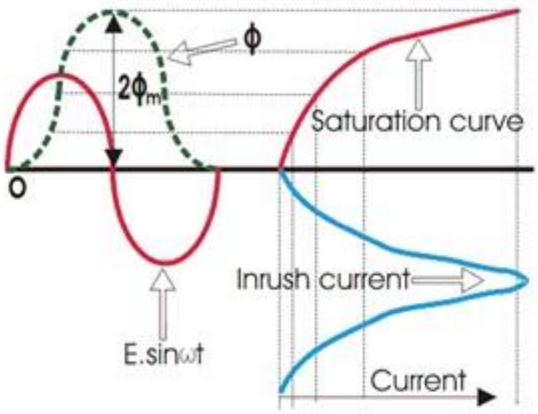


**Figure 5- Inrush Current vs Saturation Curve vs Applied Voltage**[7]

Inrush current is also dependant on the angle at which the voltage waveform is applied on the transformer. An equation which explains this concept can be derived;

Given that the resulting EMF (E) when a voltage is applied to a coil acts in the opposite direction to the applied voltage such that;

$$E = -V$$

Thus;

$$E = -V_{Max}\cos(wt + \alpha) \qquad (1)$$

Where $\alpha = \theta + \frac{\pi}{2}$, this is due to the EMF leading the Applied Voltage by 90 degrees.

E is also given by Faradays Law;

$$E = -N_1\left(\frac{d\varphi}{dt}\right) \qquad (2)$$

Equating these two equations gives;

$$-N_1\left(\frac{d\varphi}{dt}\right) = -V_{Max}\cos(wt + \alpha)$$

$$\frac{d\varphi}{dt} = \frac{V_{Max}}{N_1}\cos(wt + \alpha) \qquad (3)$$

Integrating this equation will give an equation for the flux value;

$$\varphi = \frac{V_{Max}}{N_1}\int \cos(wt + \alpha) * dt$$

$$\therefore \varphi = \frac{V_{Max}}{N_1} * \sin(wt + \alpha) + C \qquad (4)$$

C is considered to be the formation of Asymmetric Flux during energisation of the transformer. It is described by the ‘doubling effect’ and also includes the residual flux previously discussed in this document. As flux cannot instantaneously rise to its peak value, it starts from zero and reaches 1pu after ¼ cycle of voltage and continues to increase until it becomes 2pu at ½ cycle after switching (Abhilash 2016).

[7] Source - https://www.electrical4u.com/magnetizing-inrush-current-in-power-transformer/

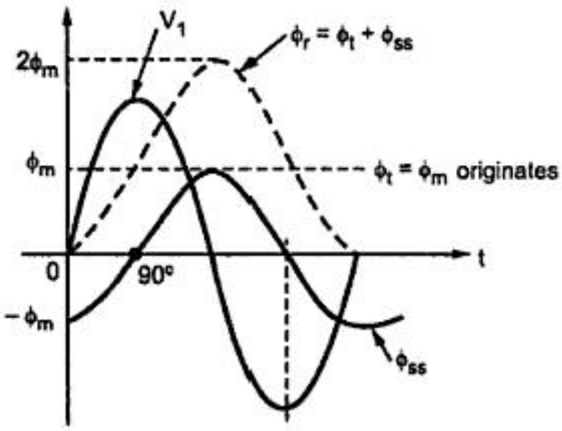


**Figure 6- Doubling Effect in a Transformer (Your Electrical Home 2013)**

The asymmetric flux can be expressed as;

$$\varphi_{residual} + \varphi_{Max} sin\alpha$$

The doubling effect is only applicable to transient periods and the maximum core flux will exponentially return to its steady state maximum value as the system transitions into steady state.

Looking back at Equation 4, it should be noted that there is a relationship such that;

$$\varphi_{Max} = \frac{V_{Max}}{N_1} \qquad (5)$$

$$\therefore \varphi = \varphi_{Max} \sin(wt + \alpha) + \varphi_{residual} + \varphi_{Max} sin\alpha \qquad (6)$$

This can now be considered as the equation for flux. From Equation 6, it can be shown that the switching angle of voltage waveform has just as much of an effect on the transformer core flux as the residual flux. If a switching angle of 0 degrees is considered with a residual flux of 0 Wb;

$$\varphi = \varphi_{\text{Max}} sin\left(wt + \frac{\pi}{2}\right) + 0 + \varphi_{Max} \sin\left(\frac{\pi}{2}\right)$$

$$\varphi = \varphi_{Max} \cos(wt) + \varphi_{Max}$$

$$\varphi = 2 * \varphi_{Max}$$

As discussed previously, this is due to the doubling effect. It can also be shown that if a switching angle 90 degrees ($\frac{\pi}{2}$) is considered with a residual flux of 0 Wb, then;

$$\varphi = \varphi_{\text{Max}} sin(wt + 0) + 0 + \varphi_{Max} \sin(0)$$

$$\varphi = \varphi_{Max} \sin(wt)$$

$$\varphi = \varphi_{Max}$$

By switching the voltage at 90 degrees, the doubling effect is completely eliminated, and as a result, the minimal transient inrush current is drawn.

Therefore, it can be summarised from this information that the transformer inrush current is also significantly affected by the switching angle of the applied voltage.

The transient inrush current of the transformer also features a large DC Component; this can be noted through analysis using Fourier series techniques on the inrush current. Due to the DC transient properties of inductors:

Inductor Time Constant ($\tau = \frac{L}{R}$),

L = Inductance of Line and of Inductor, and

R = Resistance of Winding and Source;

This means that source reactance and resistance also play a major role in the decay of the transient inrush current. A higher source resistance will mean a faster decay rate ($I = I_0 e^{-t\frac{R}{L}}$) where increases in R will decrease the duration of the transient current and slightly decrease the initial magnitude of the transient current as well. It should be noted that the resistance and reactance are considered to change in a power system between the subtransient, transient and steady states periods, thus the time constant for the rate of decay of the transient current is also considered to change between these periods.

## Annex B - Numerical Method

The numerical method detailed here can be used to gain a brief understanding of the maximum current a three-phase system might experience during the inrush period, as well as the maximum voltage dip.

$$i_{first-peak} = \frac{V_m}{\sqrt{R^2 + (\omega L_{air-core})^2}} \left( \frac{B_r - B_s}{B_n} + cos\theta + 1 \right)$$

The formula above is an early analytical calculation used to predict the first peak of inrush current.

Where:

- $V_m$ is the magnitude of the applied voltage
- ω is the angular frequency
- θ is the initial phase angle of the voltage source
- R is the series resistance
- $L_{air-core}$ is the air-core inductance of the energised winding
- $B_r$ and $B_s$ are the Residual Flux Density (flux density is also depicted by Lambda often in literature)
- $B_n$ is the peak nominal flux density.

Using this formula with regards to the equivalent transformer model connected to a transmission line, the maximum voltage dip can be calculated.

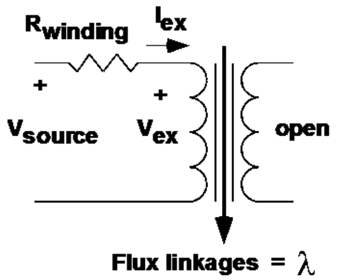


**Figure 7- Approximate Transformer Model**

Based on Figure 7, if an additional resistance is considered ($R_{Source}$) which would include the resistance of the connected transmission network, the voltage dip would be equal to:

$$V_{source-dip} = \frac{V_{source} - I_{first-peak} * (R_{source} + R_{winding})}{V_{source}}$$

This would give maximum percentage voltage dip.

A time-based equation can also be developed from the above calculation methodology.

This can be developed to create a time dependant equation that can be used to model the transformer inrush current waveform.

$$i_{peaks}(t) = \frac{\sqrt{2} V_m}{\sqrt{R^2 + (\omega L_{air-core})^2}} \cdot \left( sin(\omega t - \phi) - e^{-\frac{R}{L_{air-core}}(t - \frac{\theta_{sat}}{\omega})} \cdot sin(\theta_{sat} - \phi) \right)$$

Where;

$\theta_{sat} = \cos^{-1}\left(\frac{B_s - B_n - B_r}{B_n}\right)$

$\emptyset = \tan^{-1}\left(w * \frac{L_{air-core}}{R} + \theta\right) = phase\ angle\ between\ voltage\ and\ current\ vectors$

$\theta$ is the phase voltage angle

Applying this formula to the previous voltage dip percentage equation would give:

$$V_{source-dip}(t) = \frac{V_{source}(t) - I_{peaks}(t) * (R_{source} + R_{winding})}{V_{source}(t)}$$

Where $V_{Source}$ is the sinusoidal voltage source.

This method can be applied to each individual phase of a three-phase transformer to calculate the overall voltage dip on each phase. It should be noted that this is an estimation method only and does not give an accurate representation of the true inrush current in a three-phase system nor does it consider wider system effects.