Advances in Process Automation & Control

Practising What I Preach

J Love, 18th November 2019

Imperial College
London

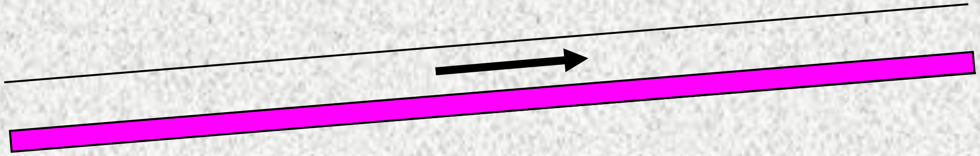
Overview

- Throughout my academic career, sanity has been provided by involvement with industry in projects that are of a design & development nature rather than research.
- This presentation provides an overview of three projects to which I have contributed:
  - slug control (BP, 10 years ago),
  - radar based early warning system (BP, 4 years ago),
  - wind turbine control system design (Crossflow Energy, current).
- Acknowledgements to BP and Crossflow for permission to present.

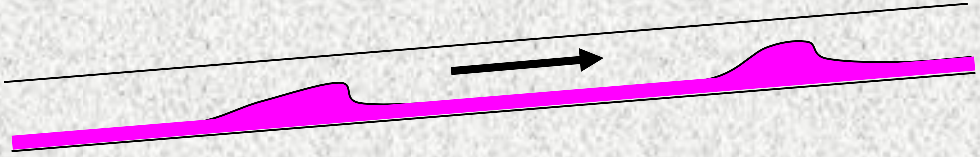
Slugging Project

- Project concerned a multiphase phenomenon that affects oil wells under certain conditions:
  - slugging is a function of fluid velocities, component fractions and pipeline geometry.
- Two main categories of slugging:
  - hydrodynamic slugging characterised by wave instability at the gas-liquid interface,
    - associated with relatively high flow rates,
  - severe slugging, characterised by periodic build-up and discharge of liquid,
    - associated with relatively low flow rates.

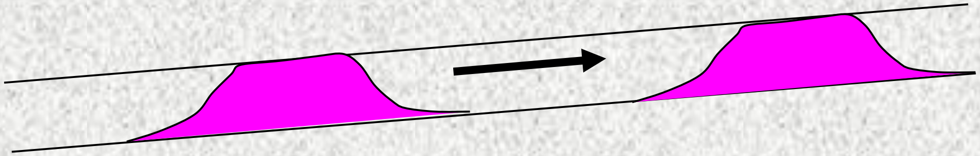
Slugging Project -2



Stratified flow



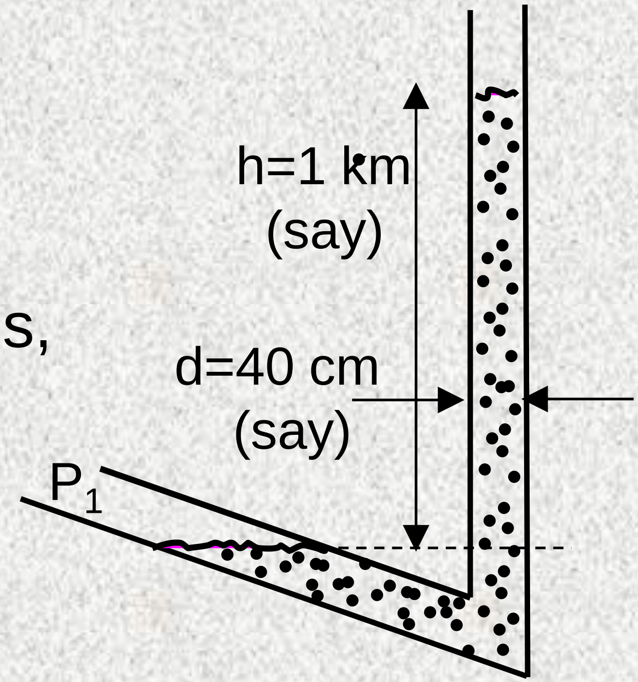
Wave instability



Plugged hydrodynamic slugging

Slugging Project -3

- During development of the slug, a dynamic equilibrium established:
  - pressure in the feed-pipe balances the head of oil in the riser,
  - as pressure builds up, head increases,
  - blowdown occurs when pressure exceeds the head,
  - slug is pushed out of riser, pressure is vented and cycle repeats.



- Size of slug in extreme case = $h.\pi d^2/4 \approx 125\ m^3$
  - pressure at bottom = $P_1 = h.\rho.g \approx 90$ bar

Slugging Project -4

- Slugging is highly undesirable for several reasons:
  - topsides: compressor overloading, poor phase separation, platform trips.
  - pipelines: stress cycling and abrasion
  - reservoirs: damage to bed (pores & interstices blocked as sand/solids broken up) due to huge pressure cycle.

Slugging Project -5

- Massive benefits from eliminating/reducing slugging:
  - typically 8 to 10% increase in throughput,
  - 5% increase in platform utilisation,
  - reduced capital costs due to less weight/space,
  - extension to field life (% not really known),
  - quicker start-up after production interruptions,
  - reduced carbon footprint per barrel.

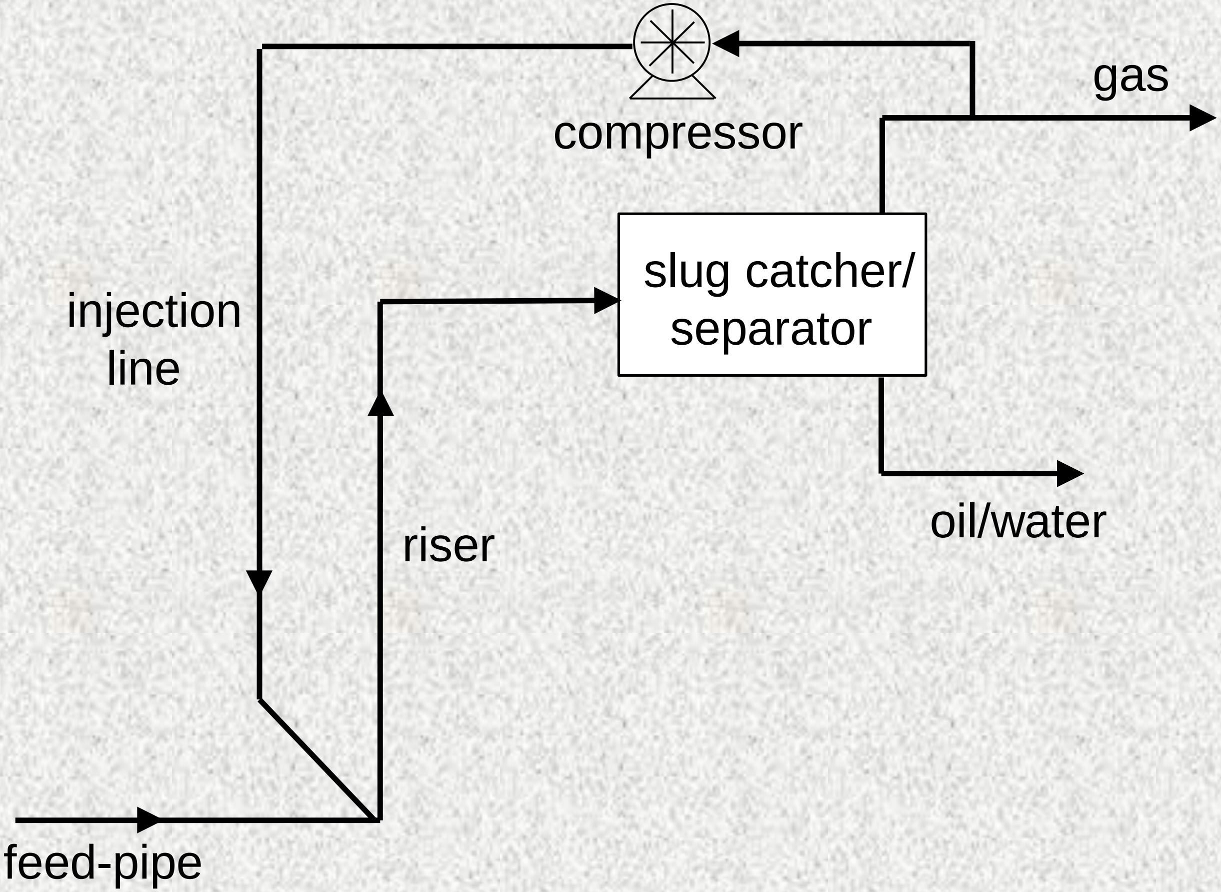
Slugging Project -6

Valhall

Slugging Project -7

- Various approaches to countering slugging but most common (hitherto) is gas injection:
  - re-compress a proportion of the product gases,
  - inject into bottom of riser down a separate, narrower pipe parallel to riser,
  - has effect of ‘aerating’ the oil: density is reduced so velocity increased,
  - velocity increases further due to expansion of gas,
  - increased velocity promotes annular flow.
- An expensive option: requires gas injection line to base of well or riser, a compressor and running costs.

Slugging Project -8



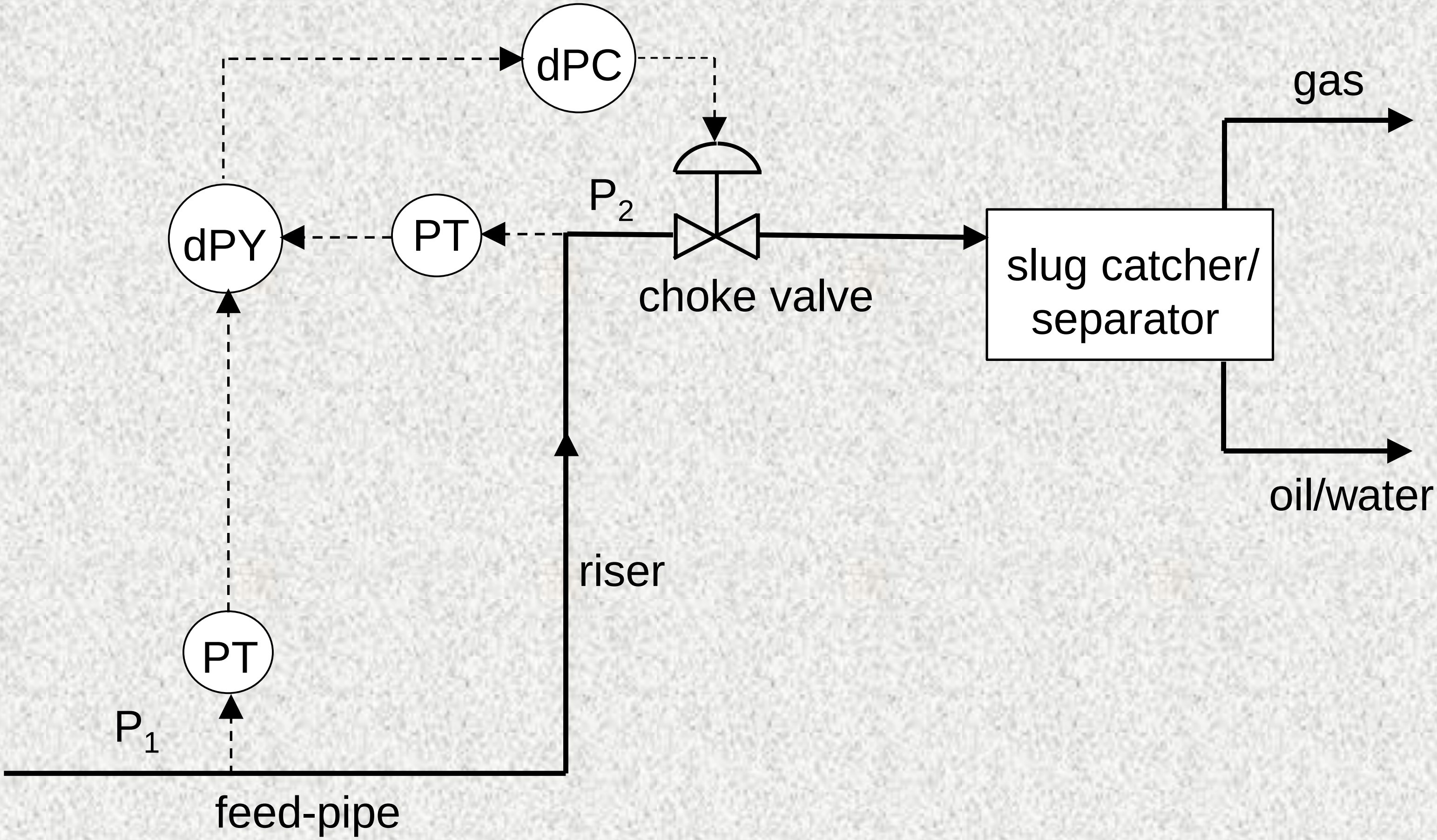
Slugging Project -9

- Alternative approach is by means of active (automatic) choking enabled by the availability (since the late 90’s) of measurements down the well:
  - instrumentation for temp, pressure and flow,
  - communications of signals to the surface.
- Project to develop an in-house universal slug control algorithm that is robust, intuitive and easily deployable.
- Algorithm development through:
  - simulation (Olga, Matlab/Simulink),
  - rig trials,
  - field trials.

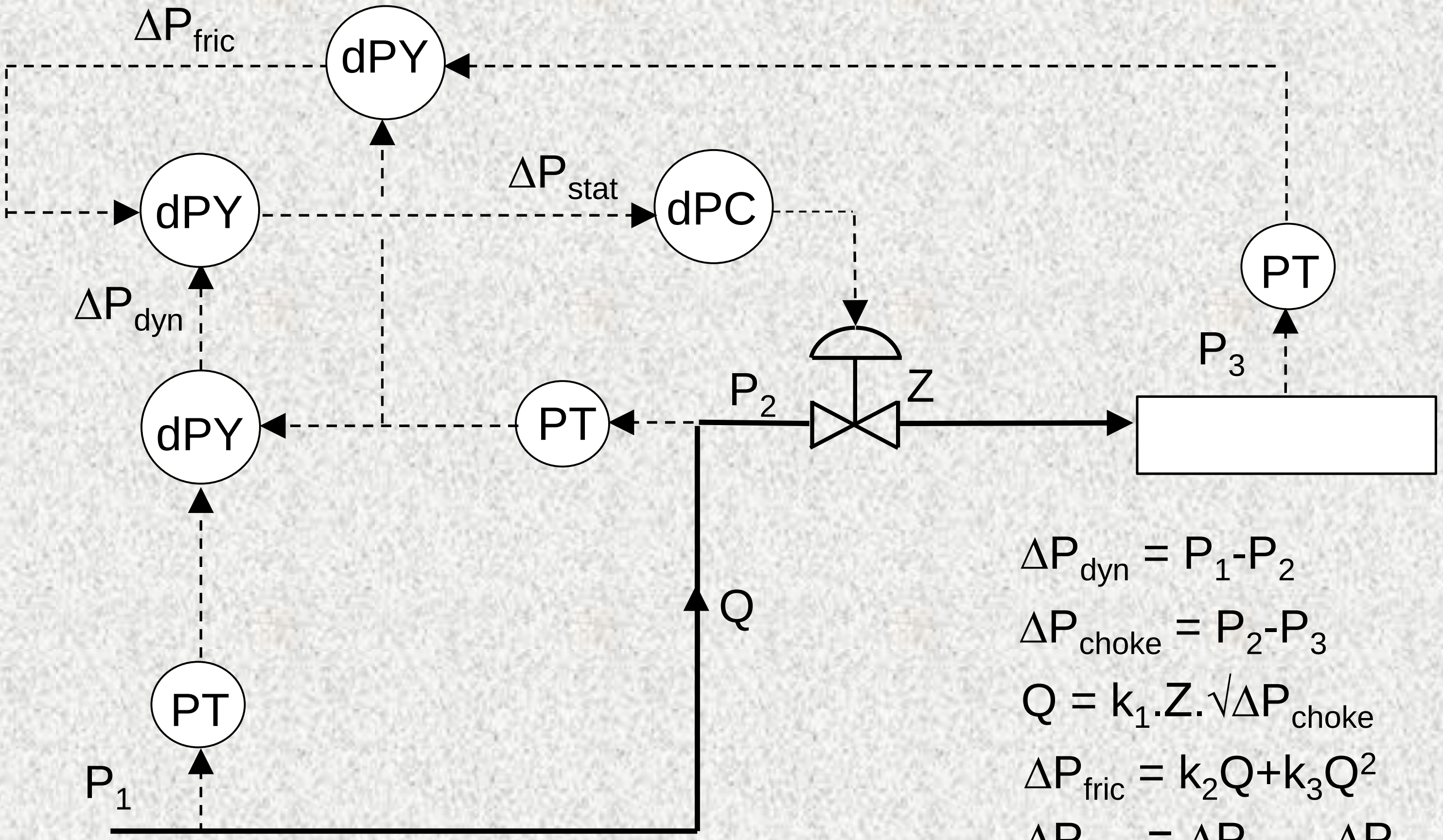
Slugging Project -10

- The basic slug control strategy is as follows:
  - measure the pressure drop ($P_1 – P_2$) across the riser,
  - control ($P_1 – P_2$) by manipulating the choke valve,
  - as the dp increases, implies static head is building up,
    - open valve to increase flow/velocities, reduces ΔP,
    - and vice versa.
- But increasing flow increases frictional losses ΔP_F,
  - effect is in opposite, wrong direction,
  - so important adaptation is to compensate for ΔP_F.

Slugging Project -11



Slugging Project -12



$\Delta P_{dyn} = P_1 - P_2$

$\Delta P_{choke} = P_2 - P_3$

$Q = k_1.Z.\sqrt{\Delta P_{choke}}$

$\Delta P_{fric} = k_2 Q + k_3 Q^2$

$\Delta P_{stat} = \Delta P_{dyn} - \Delta P_{fric}$

Slugging Project -13

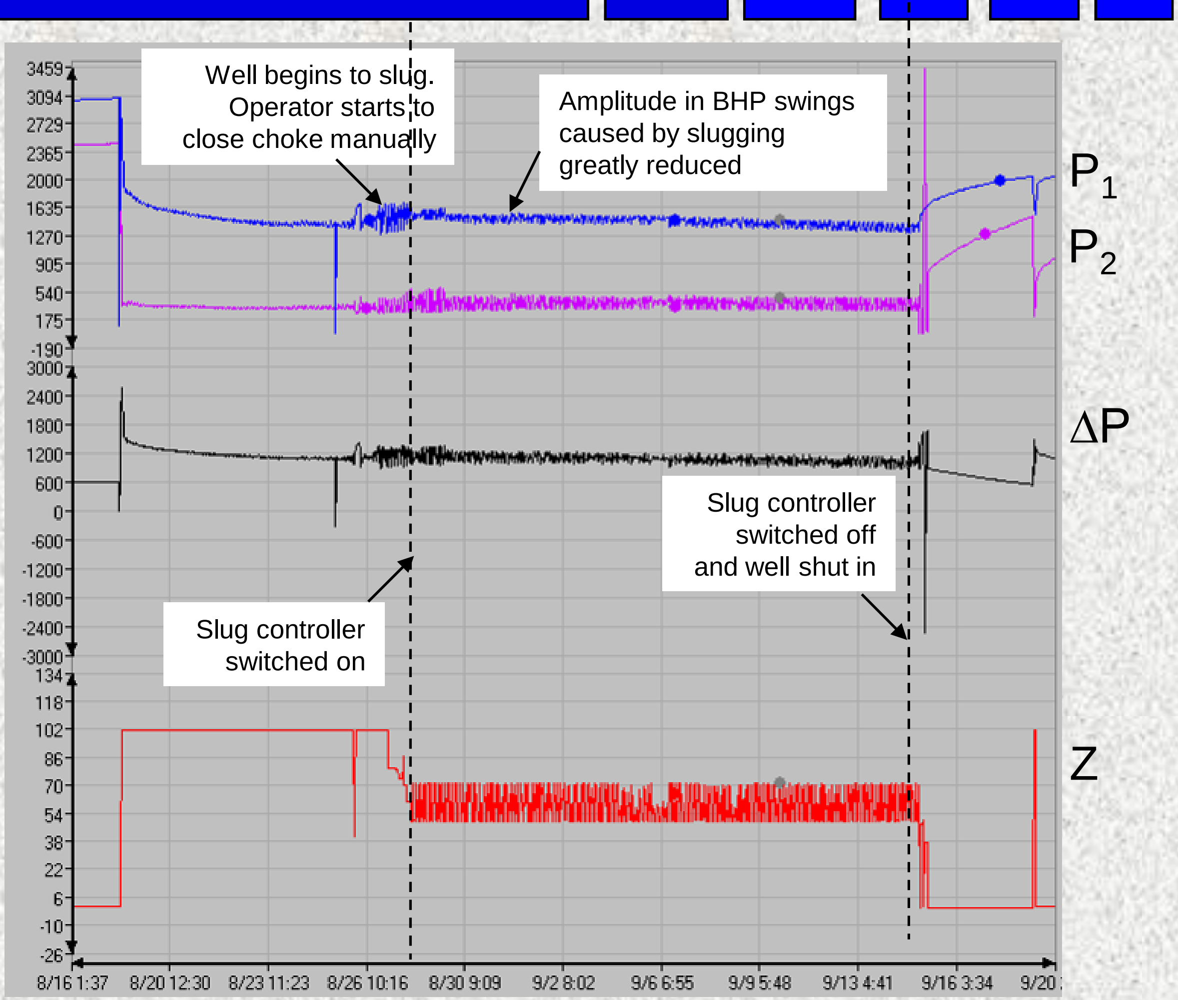
- Slug controller design was developed using Olga:
  - simulation package of choice in oil and gas industry,
  - rigorous, first principles, finite element dynamic model of severe slugging,
  - expensive (time & effort),
  - P+D controller used for stability,
  - understanding of constraints, esp choked flow,
  - initialisation issues explored.

Slugging Project -14

- Next (my contribution) was to confirm/validate design of slug controller using Matlab/Simulink:
  - model of hydrodynamic slugging in Matlab as basis,
  - control strategy developed in Simulink,
  - P+D controller used for stability,
  - basic slug control strategy plus other variants involving cascade control with slave loops for flow control.
- In parallel to this, pilot scale rig trials were carried out at Cranfield University:
  - successful, so then onto field trials on Valhall.

Slugging Project -15

Slugging Project -16



Well begins to slug. Operator starts to close choke manually

Amplitude in BHP swings caused by slugging greatly reduced

Slug controller switched on

Slug controller switched off and well shut in

Slugging Project -17

- In conclusion, the development of the algorithm is complete and proven:
  - international patent WO 2009/133343.
- The upstream O&G industry is conservative and wary of control and automation, let alone anything complex:
  - despite obvious benefits, assets initially reluctant to commit,
  - algorithm now accepted and deployment is the norm.
- Not only is control better but:
  - throughput is increased and
  - life of well is extended too!

REWS Project

- Project concerned the design and specification of radar based early warning systems (REWS).
- There are many offshore oil & gas facilities including drilling rigs, production platforms, etc. Typical risks are:
  - process safety,
  - offshore structural integrity failure,
  - subsea pipeline integrity failure,
  - loss of primary containment (LOPC),
  - errant vessel collision: various collisions & many near misses over the years,
  - helicopter incident.

REWS Project -2

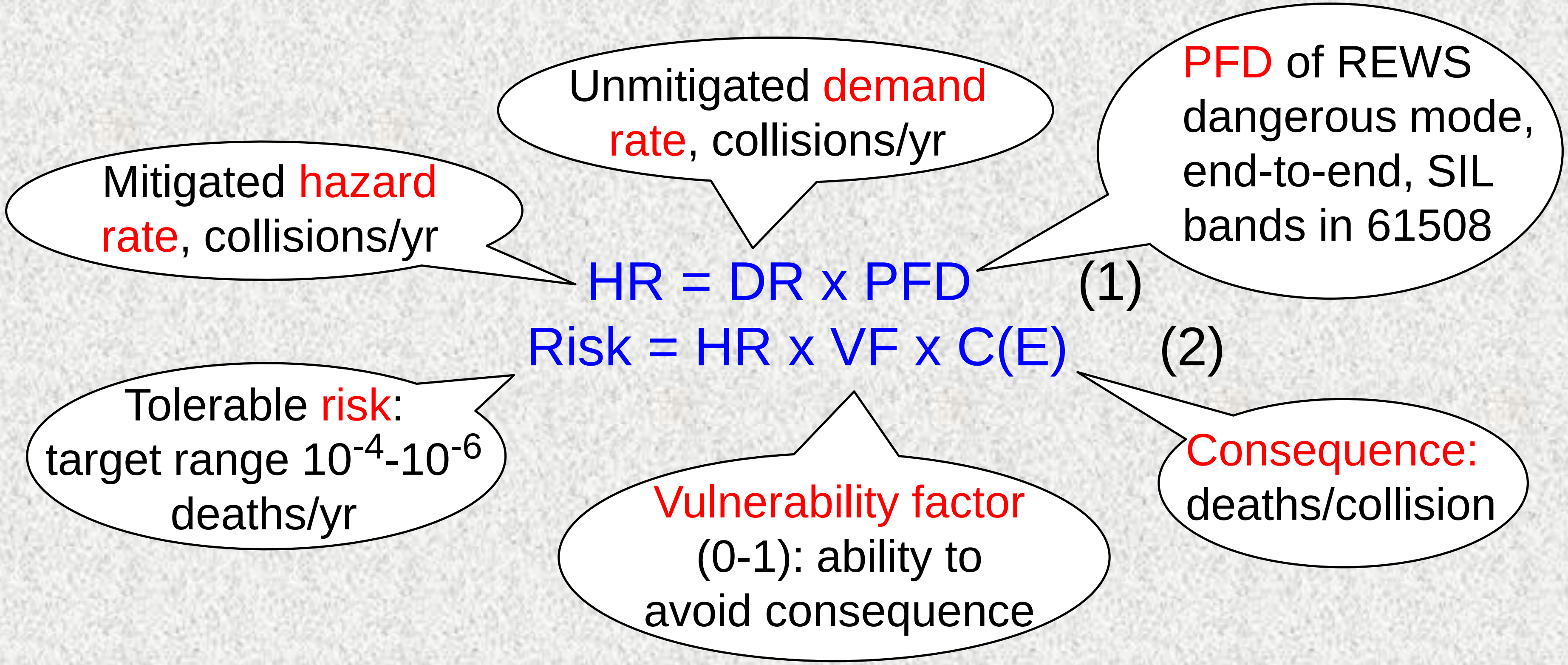
- Almost every offshore facility has a REWS whose function is to:
  - detect vessel, esp large and heavily laden, appearing over horizon (40km),
  - monitor speed and direction if on collision course or thereabouts,
  - tracking software raises alert if a realistic risk of collision is determined,
  - contact with errant vessel by radio or otherwise attempted,
  - change of course encouraged!

REWS Project -3

- Much variety in design of REWS used for collision avoidance with:
  - different types of equipment and technology,
  - multiple suppliers,
  - alternative hardware configurations,
  - various software and display configurations,
  - different levels of operator involvement, etc.
- No international standard on REWS’ requirements.
- Project was to do groundwork to enable development of internal BP standard on design & specification of REWS:
  - based upon principles of reliability engineering.

REWS Project -4

- Much of the thinking underlying project was informed and inspired by concepts of IEC 61508 and 61511!



$$HR = DR \times PFD \qquad (1)$$

$$Risk = HR \times VF \times C(E) \qquad (2)$$

Mitigated hazard rate, collisions/yr

Unmitigated demand rate, collisions/yr

PFD of REWS dangerous mode, end-to-end, SIL bands in 61508

Tolerable risk: target range 10^{-4}-10^{-6} deaths/yr

Vulnerability factor (0-1): ability to avoid consequence

Consequence: deaths/collision

REWS Project -5

- If a collision was to occur, the consequence is a function of momentum of vessel and manning level on facility.
- A collision factor was introduced/defined on basis:

$$C(E) = CF \times \text{Manning} \qquad (3)$$

- Collision factors (subject to calibration) banded according to momentum:

Momentum (kN s)	$<10^3$	10^3-10^4	10^4-10^5	$>10^5$
Collision factor (CF)	0.0005	0.005	0.05	0.5

Table 1

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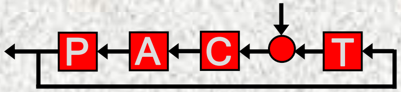


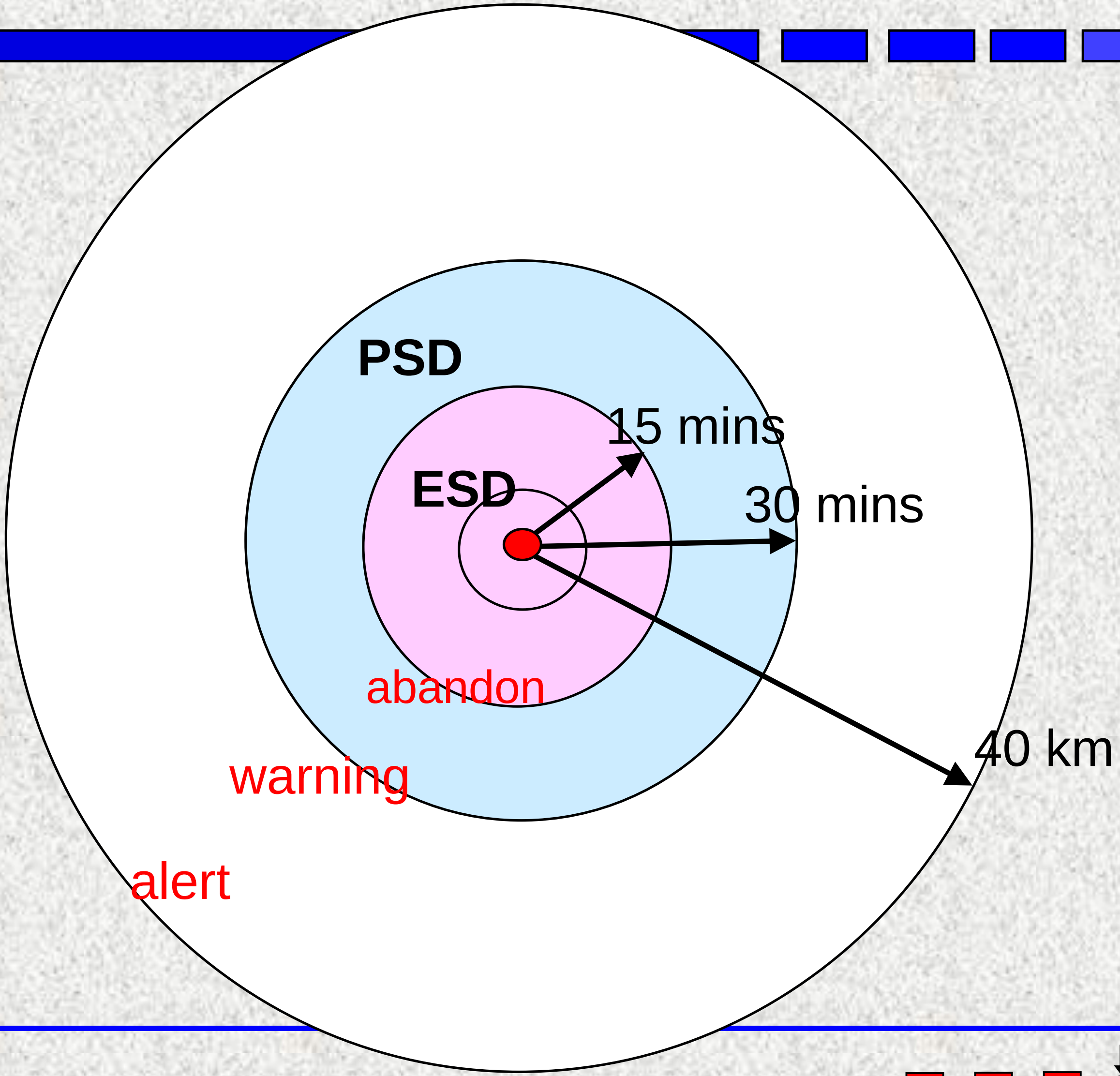
REWS Project -6

- Vulnerability allows for fact that operators may be able to avoid consequence of collision by taking to life rafts.
- Vulnerability factors (subject to calibration) proposed are:

Shutdown mode		**PSD**	**ESD**	
Alarm category	Alert	Warning	Abandon	
Distance to collision (km)	<40			
Time to collision (mins)	>30	15-30	5-15	0-5
Vulnerability factor (VF)	0.003	0.01	0.03	0.1

Table 2

REWS Project -7



REWS Project -8

- PFD articulated in bands of safety integrity level (SIL) notwithstanding that:
  - IEC 61508 & 61511 do not apply offshore, and
  - most REWS equipment is not SIL rated.
- Assumes demand mode operation (DR<1.0 collisions/yr),
  - PFD = U = 1-A

Availability	0.0-0.9	0.9-0.99	0.99-0.999	0.999-0.9999	0.9999-1.0
SIL level	0	1	2	3	4

Table 3

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REWS Project -9

- Methodology involved:
  - determine SIL required for various typical scenarios,
  - develop generic reliability models for various typical REWS configurations,
  - distinguish between alert, PSD and ESD,
  - establish that SIL required is satisfied by REWS proposed.
- Typical alert scenario: 50,000 te vessel @ 20 km/hr & 25 km away on collision course, platform has 20 personnel aboard,
  - typical ESD scenario: ditto, but only 4 km away.

REWS Project -10

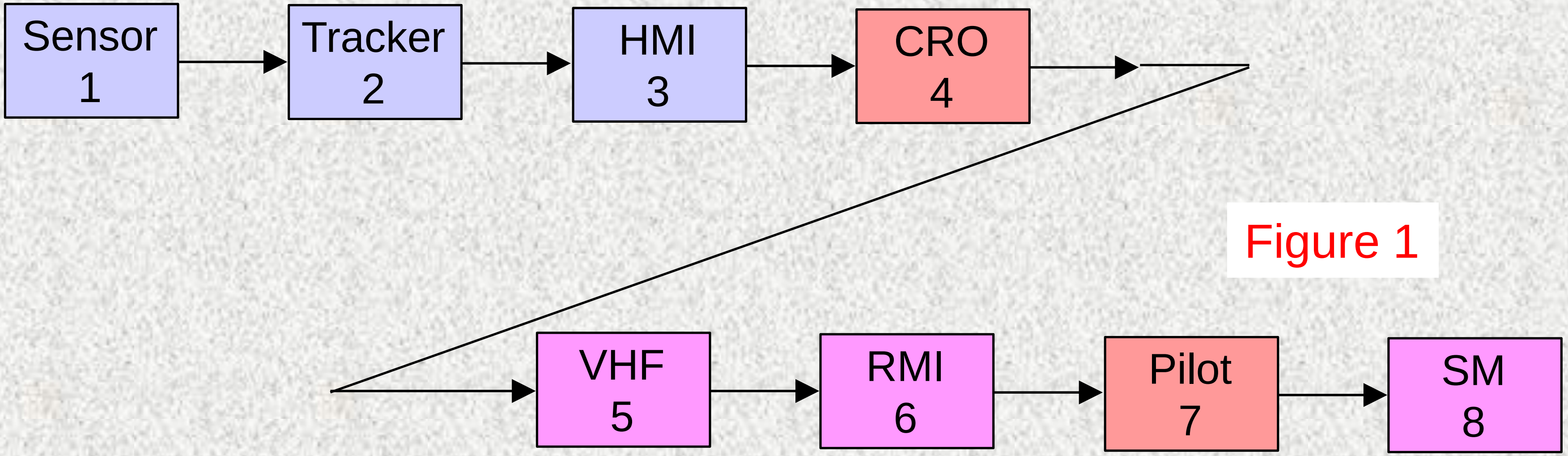
- Following formulae are used for the generic models:
  - failure rate (fpy) of elements in series: $\lambda = \lambda_1 + \lambda_2 + \ldots$
  - proof test and repair time: $PTRT = PTI/2 + MTTR$
    where PTI is proof test interval and
    MTTR is mean time to repair.
  - unavailability: $U_j \approx PTRT \times \lambda_j$
    provided MTTF>>PTRT and
    λ is for dangerous mode failures only.
  - unavailability of elements in series: $U = U_1 + U_2 + \ldots$
  - unavailability of elements in parallel: $U = U_1 \times U_2 \times \ldots$
  - availability: $A = 1 - U$

REWS Project -11

- Use historic data from industry for frequency of collisions (accidents, near misses, etc),
- Use realistic failure rate data for equipment.
- Make sensible judgements for relevant factors, eg:
  - proof test repair times,
  - human factors, eg $U_{CRO} = 0.05$.
- Especial care over parallelism: channels physically in parallel but functionally in series,
  - coverage of antennae,
  - output channels of ESD.

REWS Project -12

- In general, there are 8 sub-systems involved, end-to-end, in a REWS based collision avoidance system:



Sensor 1

Tracker 2

HMI 3

CRO 4

VHF 5

RMI 6

Pilot 7

SM 8

Figure 1

- Sub-systems are essentially in series although each box may in itself may have some parallelism.

REWS Project -13

- Sub-systems, referred to by box no, are:
  1. Sensor: comprising radar sensor, transmitter & receiver.
  2. Tracker: h/w and s/w of REWS tracking system.
  3. HMI: operator interface of REWS in control room.
  4. CRO: control room operator.
  5. VHF: means of comms between CRO and Pilot.
  6. RMI: radio machine interface on bridge of ship.
  7. Pilot: person steering the vessel.
  8. SM: steerage mechanism of vessel.
- Note: RMI, Pilot and SM are beyond facility’s control.

REWS Project -14

- The REWS configuration below is typical for alerts:

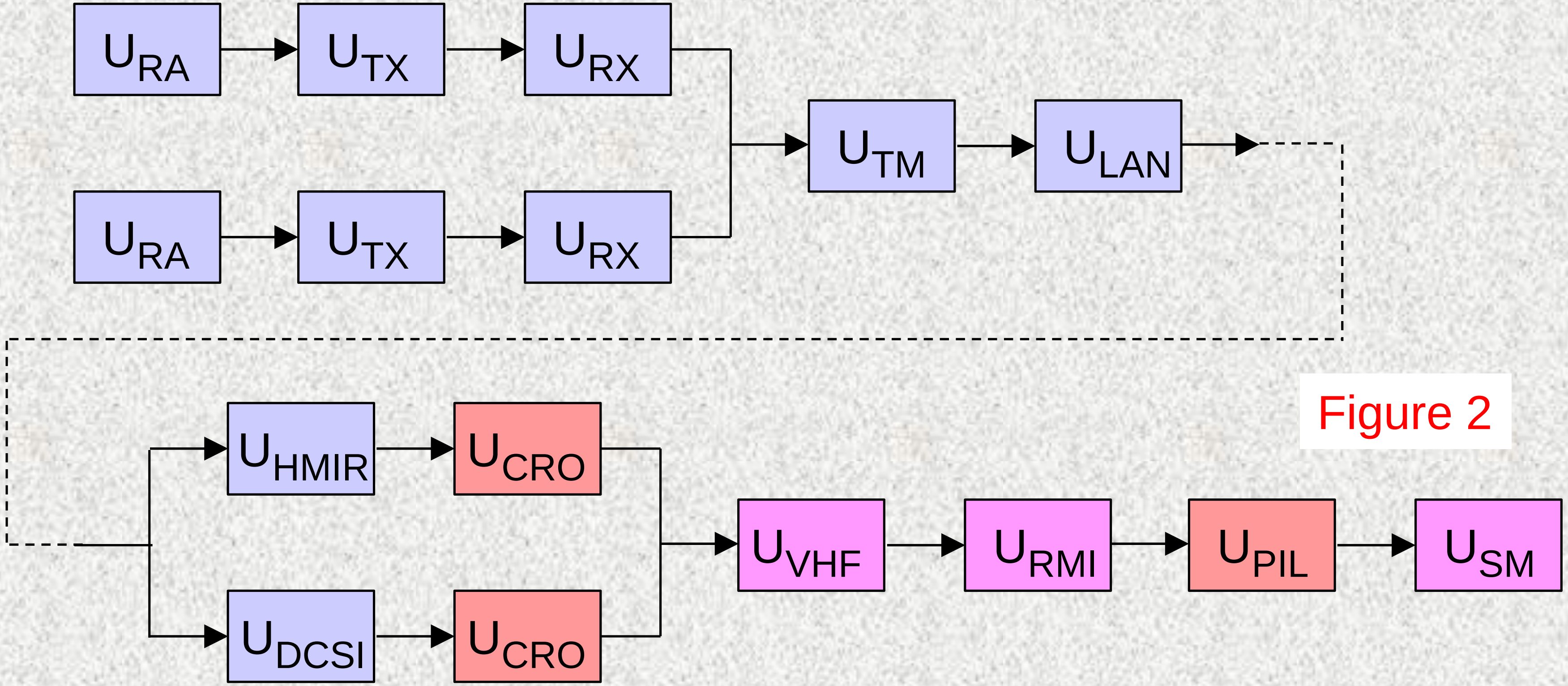


Figure 2

REWS Project -15

- The REWS configuration below is typical for ESD:

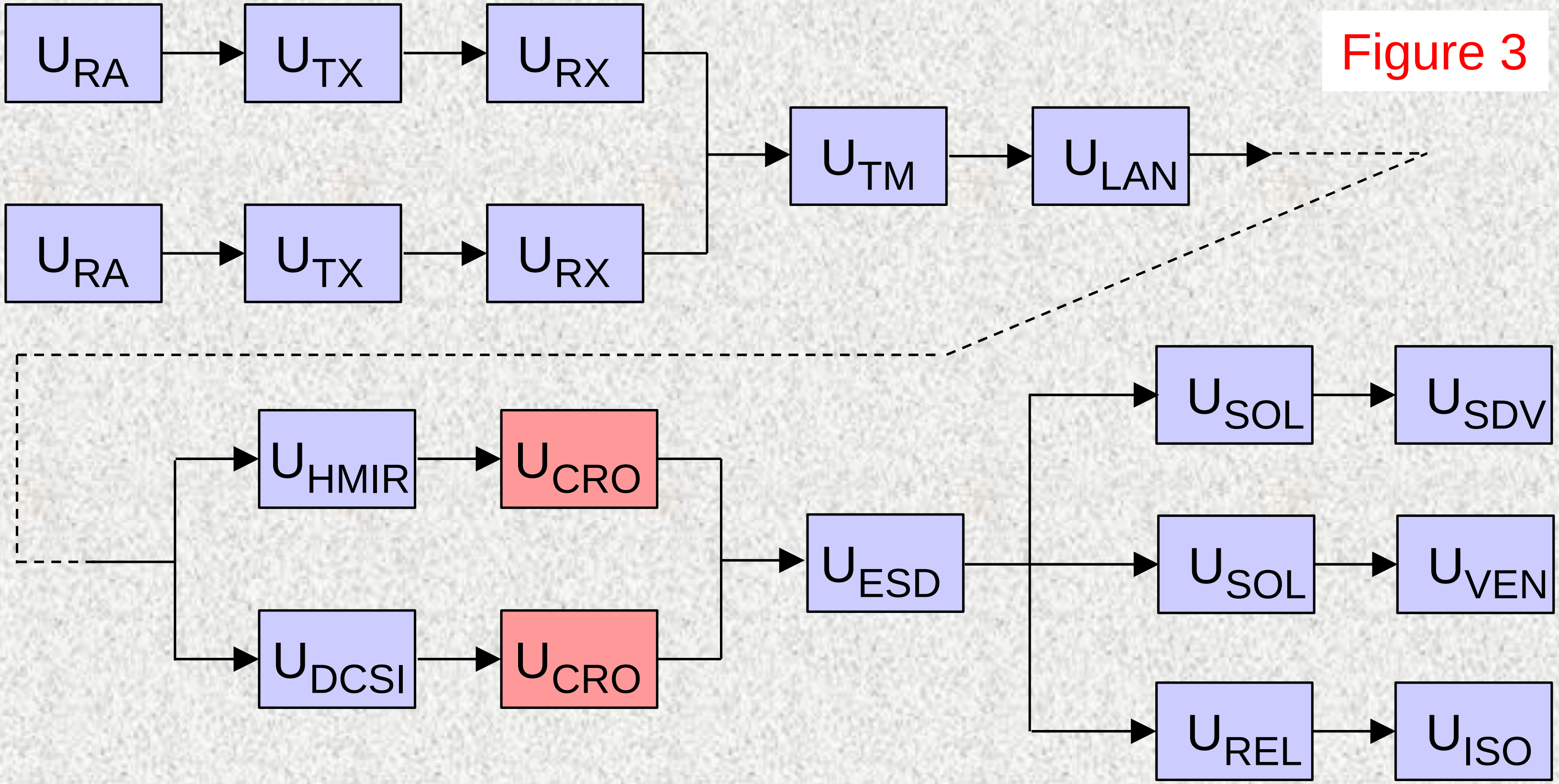


Figure 3

REWS Project -16

- In conclusion, provided insight into challenges of applying IEC 61508 and 61511 to REWS on end-to-end basis.
- Developed credible means of taking into account:
  - momentum of errant vessel,
  - distance/time to collision and consequences of such.
- Demonstrated that SIL requirements can be satisfied by REWS configurations, typically:
  - SIL 1 for alerts, ● SIL 2 for ESD.
- No need for standard to be too prescriptive in terms of technology and configuration,
  - plenty of scope for interpretation and judgement.

Turbine Project

- Project concerns conceptual design of control system for (relatively) low cost, self sufficient, low power (typically maxm of 7 kW dc) wind turbine aimed at:
  - regions where power grid is unreliable,
  - remote locations (no grid),
  - disaster zones.
- Turbine configuration consists of:
  - wind turbine,
  - solar panels,
  - diesel generator,
  - battery storage.
  - power electronics,
  - control system,

Turbine Project -2

- Turbine is cylindrical, some 2 m dia, 3-5 m length and standing some 20 m off the ground:
  - rotates about a horizontal axis,
  - convex blades along perimeter of cylinder,
  - deflector to direct wind over blades in upper half,
  - belt driven linkage to generator,
  - power electronics converts ac voltage into dc current.
- Design of turbine/blades optimised by CFD.
- The whole assembly is rotated according to wind direction and strength.
- Pre-production prototype is currently being commissioned.

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Turbine Project -4

- Overall functionality:
  - suppose the wind velocity is V m/s,
  - let the power available (capable of being generated) from the wind be P_A kW,
  - let power required (demand on the turbine) be P_R kW.
- If $P_A < P_R$ then face wind and generate P_A by manipulating both rotor speed ω and yaw angle θ.
- If $P_A > P_R$ then spill wind and shed load to generate P_R by manipulating yaw angle θ such that an appropriate relative (apparent) wind velocity V_R across blades is achieved.
- If $V > 13.5$ then spill wind by adjusting yaw θ until $V_R = 13.5$.

Turbine Project -5

- Power characteristic:
  - the relationship between power and wind speed is deterministic and depicted in Figure 1.
  - established by CFD and empirically.
- Hard constraints:
  - lower limit of 0 kW at 4 m/s,
  - upper limit of 7 kW at 13.5 m/s (47 kph).

Turbine Project -6

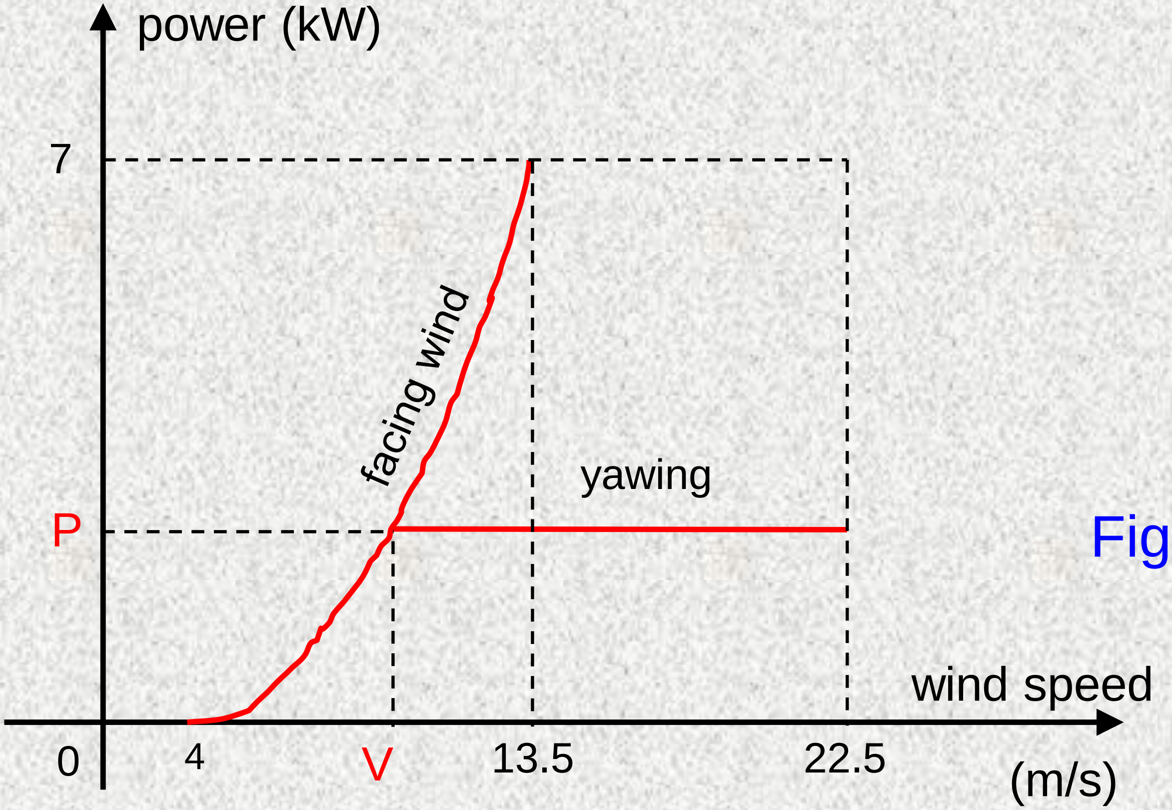


Figure 1

Turbine Project -7

- The control system is comprised of:
  - a yaw management function (YMF),
  - a cascade system (consisting of master and slave loops) for control of rotor speed ω, and
  - a simple feedback loop for control of yaw angle θ.
- YMF has three inputs:
  - change in wind direction $\Delta\theta$ deg,
  - power required P_R kW,
  - wind speed V m/s.
- YMF has two outputs:
  - rotor speed set point ω_{SP} rad/s,
  - yaw set point $\Delta\theta_{SP}$ deg.

Turbine Project -8

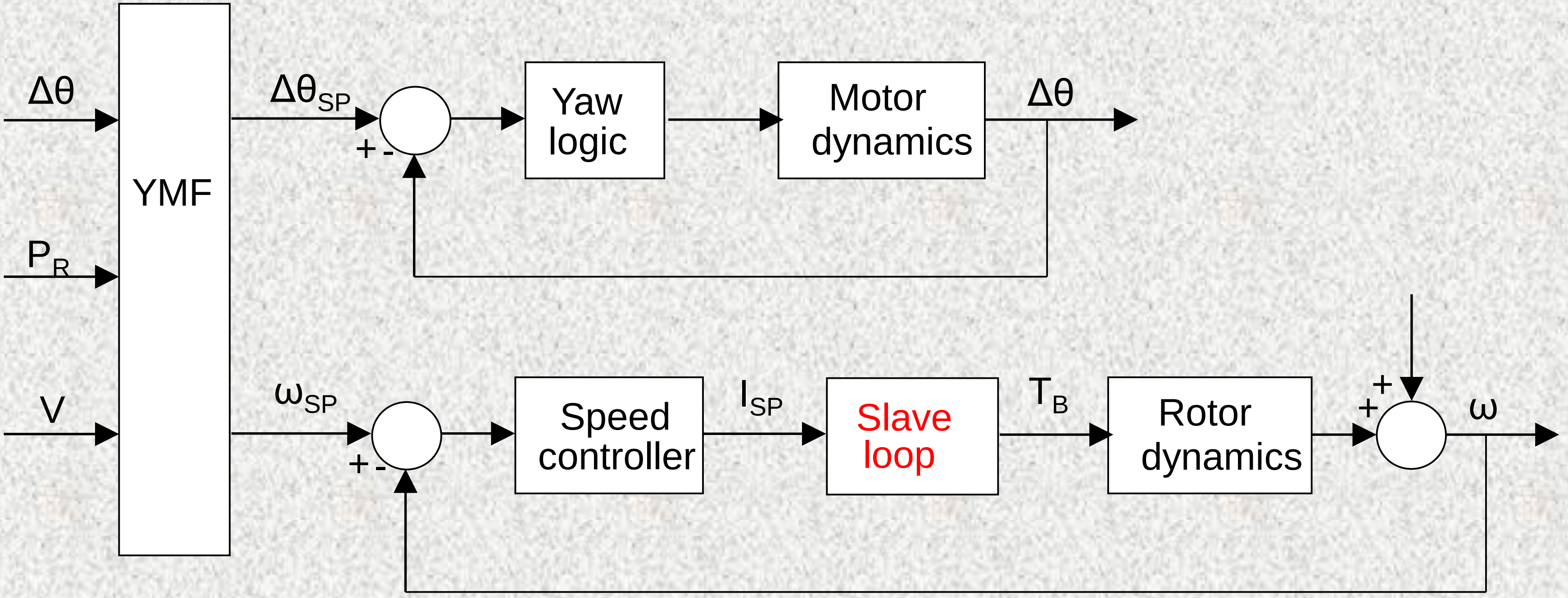
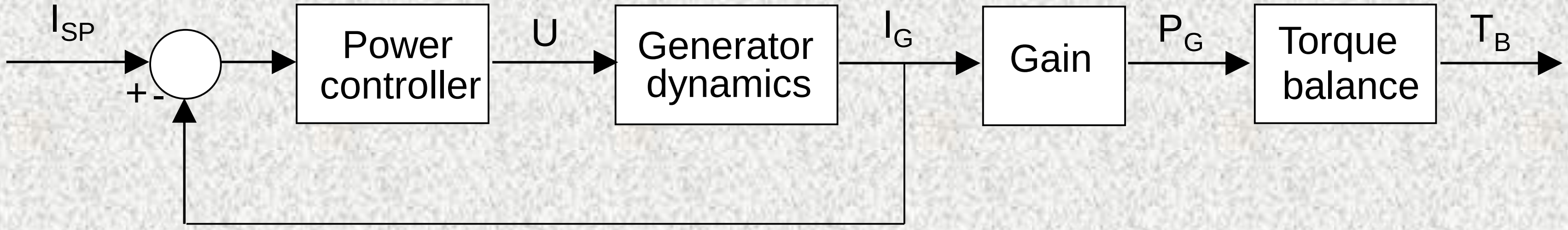


Figure 2

Turbine Project -9



Slave loop Figure 3

Turbine Project -10

- A Simulink model was used as the basis for the turbine control system design:
  - the model has the same structure as per the previous block diagrams.
- YMF has two additional outputs, $\Delta\theta_Y$ deg and V m/s, which are required for the rotor dynamics model:
  - $\Delta\theta_Y$ can be thought of as a bias on the yaw set point due to any need to spill wind.

Turbine Project -11

- Yaw management function YMF:
  - uses the power available function PAF to find P_A as per characteristic of Figure 1,
  - uses difference between P_A and P_R to decide whether to face or spill wind,
  - facing: uses function WSPF to determine ω_{SP} on basis of Figure 1 and rotor tip speed ratio (TSR) data..
  - spilling: uses ratio of V_R (apparent wind speed corresponding to P_R) to V to determine $\Delta\theta_Y$ used to bias the yaw set point.

Turbine Project -12

- Yaw logic function YLF:
  - forces output to 1, 0 or -1, subject to a deadzone of ± 5 deg.
- Generator control function GCF: contains:
  - power controller (P action only),
  - generator dynamics function GDF, a model which calculates the current I_G taken out of the generator,
  - a torque balance relating I_G to the braking torque T_B applied to the rotor shaft.
- Rotor dynamics function RDF: a model (allows for inertia, drag and braking) to determine the rotor speed ω.

Turbine Project -13

- In conclusion, the Simulink model is robust. Both loops:
  - have fast (enough) dynamics,
  - the speed control loop rejects disturbances with zero offset,
  - handle interactions well,
  - relatively easy to tune,
  - has been tested over a wide range of conditions.
- There are many approximations but, even with large changes in key model parameters, the model is robust.
- Provides confidence in basis for detailed design.

Thankyou for listening.